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EVALUATION OF THE EFFECTIVENESS OF COORDINATED RAMP METER CONTROLS

FINAL REPORT

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Samuel Sherman, UDOT ITS Division, Project Manager

16. Abstract

It has been reported that coordinating multiple ramp meters could improve the performance of ramp metering. A consulting company conducted a study for UDOT to evaluate existing coordinated ramp metering methods and determine their applicability to the Wasatch Front region and selected the Denver Helper, Minnesota Zone, and Seattle Bottleneck algorithms as the most promising candidate algorithms. UDOT desired to evaluate the cost-effectiveness of the selected algorithms against that of the local responsive ram metering that can be implemented with the existing ramp metering infrastructure. The simulation models of the tested ramp meter algorithms were prepared using the WATSim (Wide-Area Traffic Simulation) software developed by KLD Associates for a 10-mile corridor of I-15. In total, ten WATSim simulation modes were created to represent the ten cases that were evaluated—five cases for both AM and PM peak periods. Simulation analyses were conducted for the base year traffic volume (1988 volume) and for the 20-year and 40-year predicted volumes, and their results were evaluated for several measures of effectiveness. The results of the simulation analyses showed that, overall, the local-responsive ramp metering performed as effectively as the three coordinated ramp meter algorithms tested for the study site in terms of reduction in total travel time and traffic flow stabilization. Among the three coordinated ramp-metering algorithms, the Denver Helper algorithm performed best for the study site. The other two coordinated ramp-metering algorithms performed inconsistently. The performance of ramp metering is affected by various factors and the results presented in this report are site specific. Hence, additional work is needed to evaluate fully the contributions of the coordinated ramp metering methods to the entire freeway network in the Wasatch Front region. This study focused on travel time reductions and LOS stabilization of ramp metering, and the effect of ramp metering on traffic safety and the benefit of breaking up platoons of merging vehicles were not explicitly evaluated.

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1. INTRODUCTION

The report summarizes of all the work conducted by the study, especially the adaptation of the Denver's Helper algorithm, Minnesota's Zone algorithm, and Seattle's Bottleneck algorithm to the study area, the development of a ramp metering simulation software that interacts with WATSim© (Wide-Area Traffic Simulation), and the results of simulation analysis. This report also addresses the cost-effectiveness issues of adopting sophisticated coordinated ramp metering algorithms against local responsive ramp metering. The report also provides guidelines for implementing such coordinated ramp metering algorithms should the Utah Department of Transportation (UDOT) choose to use one of them.

1.1 Historical Background of Ramp Metering

Finding the solution to the ever-growing problem of traffic congestion is the goal of many city planners across the United States. Though the solution to traffic congestion will probably elude us for many years to come, certain measures have been employed to alleviate the problem. Building new roads, constructing more lanes on existing highways, introducing HOV lanes, implementing Intelligent Transportation Systems (ITS) on current systems, and improving public transit services have all helped transportation agencies reduce congestion.

Ramp metering is one example of a congestion-mitigation measure. The ramp meter was introduced in the early 1960s in experiments conducted in Detroit, New York, and Saint Louis (Bogenberger & May 1999). Since then, the ramp meter has spread across the United States and to other countries (see Table 1.1), providing some relief to the problem of congestion. The dictionary defines the verb "meter" as "to supply in a measured or regulated amount." The ramp meter is a type of traffic signal designed to improve traffic flow on freeways by regulating how quickly cars enter from on-ramps. The meter allows only one vehicle to enter a highway at a time, delaying the next car for up to 15 seconds (see Figure 1.1).

For illustrative purposes, the following paragraphs describe the benefits of ramp metering in a number of cities across the U.S. (listed below). The specific ramp meter methods that were evaluated for this study are discussed later in the report.

- Portland, Oregon
- San Diego, California
- Minneapolis/St. Paul, Minnesota
- Austin, Texas
- Seattle, Washington
- Denver, Colorado
- Detroit, Michigan
- Long Island, New York

Table 1.1 Ramp metering systems in the U.S.
(Source: FHWA 2001b)

Metropolitan Area		Number of Meters	Miles of Meters
Arizona	Phoenix	65	N/A
California	Fresno	15	12
	Los Angeles	808	700
	Orange County	278	258
	Sacramento	19	22
	San Bernardino	51	71
	San Diego	134	126
	San Francisco	96	118
Illinois	Chicago	109	136
Michigan	Detroit	49	32
Minnesota	Minneapolis	367	160
New York	Long Island	75	35
Virginia	Arlington	26	32
Washington	Seattle	54	N/A
Wisconsin	Milwaukee	43	32

Figure 1.1 Ramp meter and close-up of signal.
(Source: FHWA 2001b and ITS International 2001)

Portland, Oregon. Portland was the first city to install ramp meters in the Pacific Northwest (Piotrowicz & Robinson 1995). The ramp meters were installed along a 10-kilometer stretch of Interstate 5 (I-5) to help alleviate congestion and increase the average speed around the PM peak. Before the installment of the ramp meters the PM peak speed between downtown Portland and the Washington state line was an average of 26 kph

(16.3 mph). The Portland Department of Transportation installed 16 metered ramps to reduce congestion and increase the overall speed during the congested period. The following list illustrates the benefits that Portland has seen since the installment of the metered ramps:

- Increase in PM peak speed from 26 kph (16.3 mph) to 66 kph (41.3 mph) in 14 months
- Travel time reduced from 23 minutes (but highly variable) to about 9 minutes
- Fuel consumption caused by ramp delay reduced by 2040 liters (540 gallons) of gasoline per weekday
- Overall accident rates during the peak period reduced by 43%

Portland has seen a dramatic change in the way traffic flows around I-5. Because of the success of metered ramps city has installed more ramp meters around the city and in neighboring areas. Currently there are over 50 ramp meters in and around Portland (Piotrowicz & Robinson 1995).

San Diego, California. The first ramp metering system in San Diego was initiated in 1968. The system, run by the California Department of Transportation (CalTrans), includes over 130 ramp meters on a total of 110 plus kilometers (69 plus miles) of freeway (FHWA 2001b). No real evaluations have been made on the system, but sustained volumes of 2200 vph to 2400 vph, and occasionally even higher, are common on San Diego metered freeways, as well as increased speeds on average of 96 kph (60 mph) (FHWA 2001b). A noteworthy aspect of the system is the metering of freeway-to-freeway connector ramps. Metering freeway-to-freeway connectors requires many important considerations, such as storage space, advanced warning, and sight distance.

Minneapolis/St. Paul, Minnesota. The Twin Cities Metropolitan Area first installed ramp meters in 1969. As of the year 2000, the Minnesota Department of Transportation (Mn/DOT) used approximately 430 ramp meters to manage freeway access on approximately 336 km (210 miles) of freeways in the Twin Cities metropolitan area (Cambridge Systematics et al. 2001). The first two ramp meters were put in on I-35E north of downtown St. Paul. Others were later added on an 8-kilometer (5-mile) stretch of I-35E and I-35W, and they are evaluated periodically. Since the installments of the ramp meters, the Twin Cities have benefited in the following ways (Piotrowicz & Robinson 1995):

- Speeds on I-35E increased by 16% from 60 to 69 kph (37.5 to 43.1 mph)
- Peak period accidents decreased by 24% and peak period accident rates decreased by 38% (on I-35E)
- Speed on I-35W increased by 35% from 55 to 74 kph (34.4 to 46.3 mph)
- Peak period accidents decreased by 27% and peak period accident rates decreased by 38% (on I-35W)
- Peak period pollutant emissions decreased to just under 2 million kilograms per year (4.4 million pounds)

The Twin Cities underwent a shutdown study in the fall of 2000 in response to the legislative mandate to determine the effectiveness of its ramp meters. The study concluded that the benefits in dollar amounts outweighed the cost (see Table 2) (Cambridge Systematics et al. 2001).

Table 1.2 Cost/benefit analysis results for the Minnesota ramp metering system.

Measure	Value
Annual ramp metering benefits	$40,028,008
Annual ramp metering costs	$7,877,275
Annual net benefit (benefits - costs)	$32,150,734
Benefit/cost ratio	5.1:1

Source: Cambridge Systematics et al. 2001

Austin, Texas. Texas first installed ramp meters in the late 1970s along northbound I-35 (FHWA 2001a). The initial system consisted of three metered ramps set for the AM peak period. The following list illustrates the benefits of those first metered ramps (Piotrowicz & Robinson 1995):

- Metering increased vehicle throughput by about 7.9%
- Average speed increased by 60%

Seattle, Washington. The Washington Department of Transportation (WSDOT) employed its first ramp metering system in the fall of 1981 along I-5 north of the Seattle Central Business District (Piotrowicz & Robinson 1995). The system, named FLOW, initially included 17 southbound metered ramps for the AM peak and 5 northbound metered ramps for the PM peak. There were more than 50 ramp meters in use and more meters were planned when Piotrowicz and Robinson reported. Since the meters were installed, Seattle has experienced the following benefits:

- Travel time dropped from around 22 min to 11.5 min
- Accident rates decreased by 39%
- Traffic on surrounding routes decreased by 43% due to increased accessibility

Denver, Colorado. The Colorado Department of Transportation ran a pilot project to test the usefulness of the ramp metering system along I-25 in the spring of 1981 (Piotrowicz & Robinson 1995). The system in place consisted of five metered ramps that operated during the AM peak along a stretch of 4.7 kilometers (2.5 miles) of the Interstate. The DOT tested the area for about 18 months and concluded the following:

- Average peak period driving speed increased by 57%
- Average travel time decreased by 37%
- Accidents declined by 5%

The pilot project proved to be a success, causing the Colorado DOT to install more ramp meters. During an evaluation of the system to prepare for daylight savings time, all the ramp meters were reset, but the central computer was not. Consequently, the area suffered the worst traffic congestion in years. Since then, the media have appreciated the implementation of the metering systems in Colorado, giving it rave reviews (Piotrowicz & Robinson 1995).

Detroit, Michigan. The Michigan Department of Transportation (MDOT) installed some of its first meters around November of 1982. The system has since grown to over 40 metered ramps across the state (Piotrowicz & Robinson 1995). Michigan State University conducted an evaluation of the metered system and concluded the following:

- Speed increased by 8%
- Peak hour volume increased by 6400 vph from 5600 vph
- Accident rates decreased by 50%
- Injury accidents decreased by 71%

The evaluation showed the positive impact of the metered ramps. Eventually, MDOT decided to install more ramp meters. In an article published in Michigan, an announcement was made that more meters would be implemented and that an evaluation would be made on the current system along I-75 (Kang & Gillen 1999).

Long Island, New York. In 1989, Long Island Expressway's ramp meter system was evaluated after two months in operation to determine its effectiveness (Piotrowicz & Robinson 1995). The following are the results of that evaluation:

- Peak period mainline travel time decreased by 20%, from 26 to 21 min
- Average speed increased by 16%, from 47 to 56 kph (29.3 to 35.0 mph)
- Motorists entering the system experienced a 13.1% reduction in travel time
- Motorists entering the system experienced an increase in average speed from 37 to 45 kph (23.1 to 28.1 mph)
- 6.7% reduction in fuel consumption
- 17.4% reduction in carbon monoxide emissions
- 13.1 % reduction in hydrocarbons

The metering system in Long Island has brought about significant benefits since its implementation in the area. It has improved the way the traffic flows and has reduced the amount of pollutants in the air.

The metering of ramps can significantly improve the way traffic flows. As analyzed in the case studies mentioned above, metering consistently increases travel speeds on metered facilities (from 16% to 62%) and increases travel time reliability. Ramp meters also decrease the amount of accidents that occur (from 24% to 50%), as well as the amount of air pollutants caused by emissions. Ramp metering alone will not solve the problem of congestion, but when used effectively with a well planned and operated system, it will undoubtedly be a part of the solution.

1.2 The Need for Ramp Metering in the Wasatch Front Region

During the morning and evening peaks, some portions of the freeway system in the Salt Lake County metropolitan region have experienced severe congestion, although such congestion may last for a shorter period than in other metropolitan regions in the U.S. The implementation of ramp metering along the Wasatch Front is one option of the Advanced Transportation Management System (ATMS) currently being deployed by UDOT. The purpose of the ATMS is to reduce traffic congestion, primarily within the freeway network shown in Figure 1.2. Ramp metering has been proven in other parts of the country (see section 1.1) and around the world to be an effective tool in reducing and delaying the onset of traffic congestion through forced offline storage and reduced merging turbulence. As such, a comprehensive, coordinated metering system has been proposed as part of the ATMS deployment.

According to UDOT's plan, the implementation of ramp metering along the Wasatch Front will follow a segmented deployment schedule, with the following priorities used for deployment in the near-term future (TransCore 1999):

1. The north I-15 corridor in Davis County, northbound (NB) and southbound (SB), from Beck Street to Kaysville.
2. The I-15 corridor through Salt Lake County, NB and SB, from 1300 South to 10600 South.
3. The west side of the I-215 Belt Route, NB and SB, from the I-15 South Interchange to 700 North.
4. The east side of the I-80 corridor, eastbound (EB) and westbound (WB), from the I-15 interchange to Foothill Boulevard.
5. The east side of the I-215 Belt Route, NB and SB, from the I-15 south interchange to Parleys Canyon.

To implement this program, a study was needed to evaluate existing coordinated traffic responsive ramp metering algorithms and determine their applicability to the Wasatch Front. UDOT hired TransCore, a consultant, to conduct the algorithm evaluation study. TransCore identified three coordinated ramp metering algorithms that are suitable to the freeway system in the Salt Lake City metropolitan region (TransCore 1999).

Once the three algorithms were chosen, UDOT desired to evaluate the cost-effectiveness of these three algorithms against local responsive ramp metering that can be implemented with the existing ramp metering infrastructure. This can only be done by simulation.

A team consisting of researchers from Brigham Young University, the University Utah, and KLD Associates, the developer of WATSim© (Wide-Area Traffic Simulation) software, was formed to conduct the study.

Figure 1.2 Freeway network in the Salt Lake County metropolitan region.
(Source: http://www.utahcommuterlink.com, Accessed 5/24/2002)

1.3 Evaluation of On-Ramp Control Algorithm by the University of California

A similar study to evaluate the performance of coordinated ramp metering methods was conducted by the Institute of Transportation Studies of the University of California, Davis about the same time this study was undertaken (Zhan et al. 2001). In the study the Paramics (PARAllel MICroscopic Simulation) simulation software was used to evaluate the performance of ALINEA, Bottleneck, SWARM, and Zone algorithms. A stretch (about 5.9 miles) of Interstate 405 in Orange County, California was used as a test site (see Figure 1.3), and the simulation was done for a two-hour simulation period, consisting of four 30-minute simulation intervals. The simulated stretch contained six interchanges.

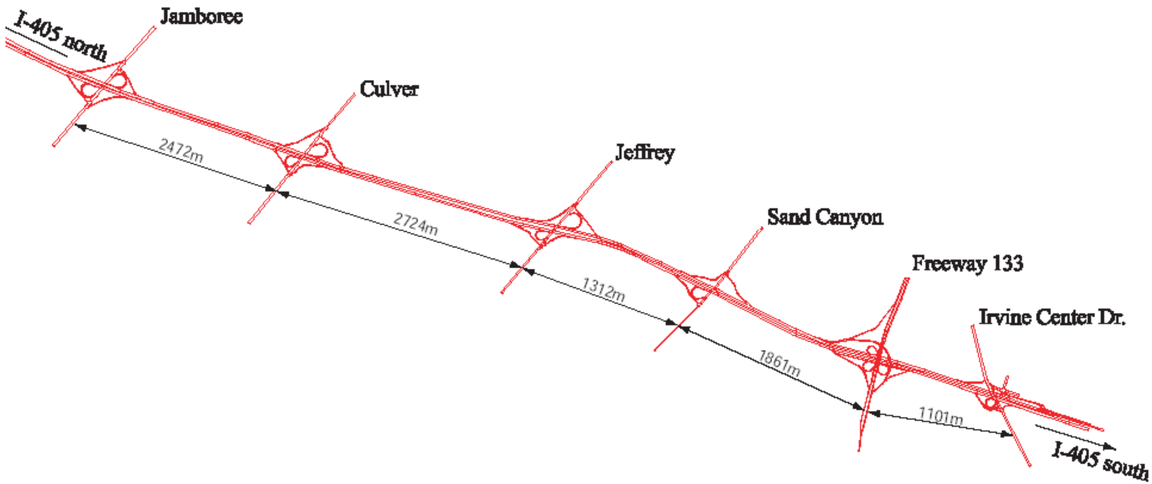

Figure 1.3 Configuration of simulated network on I-405.
(Source: Zhang et al. 2001)

Using the total vehicle travel time as the measurement of effectiveness (MOE), they concluded that (Zhang et al. 2001):

- Compared with no metering, ramp metering reduces the total vehicle travel time up to 7%. The effectiveness of a ramp control algorithm depends on the level of traffic demand. As traffic demand increases, ramp metering tends to be more effective in reducing system travel time.
- No significant performance differences exist among ALINEA, modified Bottleneck, modified SWARM with one time-step-ahead prediction, and Zone algorithm under the tested scenarios.
- Modified SWARM with five-step-ahead prediction has the poorest performance among all tested algorithms due to the inaccuracy of the five-step-ahead prediction model. This indicates that a good traffic prediction is the key to SWARM's performance.
- Coordinated ramp metering algorithms do not necessarily perform better than local control algorithms if some of their key parameters are not well calibrated. Well-tuned parameters are critical to good ramp metering performance.
- Ramp metering performance and parameter values are non-linearly related. There is a broad range of parameter values over which ramp metering performance does not change significantly. Outside of this range, however, ramp metering performance deteriorates quickly.
- Ramp metering seems to be more effective under certain demand patterns than others.

The last conclusion can be interpreted as "demand patterns do affect the performance of the tested ramp metering algorithms."

Zhang et al. (2000) also identified issues that need to be considered in designing a ramp metering system:

- A systematic procedure to calibrate complex ramp metering algorithms needs to be developed.
- A proactive ramp metering algorithm requires accurate predictions of traffic conditions.
- Traffic demand patterns affect the performance of ramp metering.
- Ramp metering may yield greater benefits if it is integrated with queue management, traveler information, and arterial street signal coordination in a corridor setting.

1.4 Report Organization

This report summarizes the results of all the tasks carried out in the study and consists of eleven chapters, including this introductory chapter. Chapter 2 presents the scope of work for the study. Chapters 3 and 4 present the results of a literature search, focusing on metering theory and a description of the three algorithms selected for the Salt Lake Country metropolitan region (Denver's Helper algorithm, Minnesota's Zone algorithm, and Seattle's Bottleneck algorithm). Chapter 5 describes the conditions of the study site and the results of a travel-time study, followed by Chapter 6 presenting the simulation study methodology used in the study. Chapter 7 is the heart of this report and discusses the results of simulation analyses and the implications of the results. Chapter 8 presents the conclusions of the study, and Chapter 9 offers policy and operation related recommendations.

Appendices A, B and C describe the process for adapting the Denver's Helper algorithm, Minnesota's Zone algorithm, and Seattle's Bottleneck algorithm to the study site, respectively. Appendix D discusses the simulation model preparation process, Appendix E presents the development of the Ramp Meter Simulation System software, and Appendix F describes the data input steps for the three algorithms.

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2. SCOPE OF STUDY

This study compares the effectiveness of three currently deployed coordinated ramp metering algorithms (the Denver Helper algorithm, the Minnesota Zone algorithm, and the Seattle Bottleneck algorithm) against local responsive ramp metering and no-metering cases using simulation. The three algorithms used in this study were selected by TransCore in a previous ramp-meter related study (TransCore 1999) as best suited for the stretch of I-15 in the Wasatch Front region. The rankings of these three coordinated algorithms were close to each other, and TransCore did not place them in a certain ranking order.

KLD Associates, the developer of the WATSim© traffic simulation model, created a ramp meter evaluation software that will execute these coordinated algorithms. Volume and occupancy data are extracted from WATSim© simulation, processed by the algorithm selected by the user, and the ramp metering rates are sent back to the ramp meters in the WATSim© simulation while simulation continues at every 20 to 30 seconds depending on the algorithm. The development of the application software, called the Ramp Meter Simulation System (RMSS), is the result of the teamwork between the researchers of Brigham Young University, the University of Utah, KLD Associates, and UDOT.

The simulation analysis portion of the study evaluated the following four null hypotheses (H_0):

1. Local responsive ramp metering will not improve the operation of the freeway over the no-metering case.
2. Coordinated ramp metering algorithms will not improve the operation of the freeway over the no-metering case.
3. Coordinated ramp metering algorithms will not improve the operation of the freeway over local responsive metering.
4. The three coordinated metering algorithms will yield results that show no statistically significant differences in the selected measures of effectiveness among them.

These four hypotheses were tested by modeling the following five simulation cases:

- Base case—no metering
- Local responsive metering (the local responsive metering portion of the Denver algorithm was used to represent the local responsive metering for the Wasatch Front)
- Denver Helper algorithm
- Minnesota Zone algorithm
- Seattle Bottleneck algorithm

A real-world network segment of I-15 in Davis County, Utah, was used as a study site. The large-scale simulation model involved a 10-mile stretch of freeway with 6 interchanges (including the unmetered I-215/I-15 junction) with twelve 15-minute simulation intervals to model a three-hour peak period both in the morning (6:00 AM – 9:00 AM) and in the evening (3:00 PM – 6:00 PM). See chapter 5 for the description of the study site and chapter 6 for simulation model preparation efforts.

2.1 Study Tasks

This study performed the following major tasks:

- Literature search focusing on-ramp metering algorithms and the effectiveness of ramp metering
- Field observation to obtain the geometric, traffic, and control conditions for the study site and t o collect data that were not available from UDOT. A travel time study is also conducted.
- Development of a simulation model network for the study site (preparation of WATSim© simulation input files for the studied ramp metering schemes)
- Adaptation of the Denver's Helper algorithm, Minnesota's Zone algorithm and Seattle's bottleneck algorithms to the study site
- Development of a ramp meter simulation system (RMSS) that collects volume data from vehicle detectors in the WATSim© model, processes the data using a ramp meter algorithm selected by the user, and sends ramp metering rates back to the ramp meters in the WATSim© model while the simulation runs at a specified time interval
- Design of experiment to test the aforementioned hypotheses and make multiple runs to collect necessary MOE data from simulation runs
- Analysis and comparison of MOEs to test the aforementioned four hypotheses and evaluate the cost-effectiveness of coordinated ramp meter controls over local responsive meter control
- Preparation of ramp meter guidelines for UDOT to consider

3. METERING THEORY

As an aid in understanding the metering study discussed in this report, the following sections present the theory of design, construction, and operation of ramp meters.

3.1 Introduction to Metering Theory

Since the first ramp meters were installed in the 1960s, several DOTs around the country have developed expertise in the deployment and operation of metered systems. DOTs in California, Minnesota, Wisconsin, Michigan, Illinois, and Washington have all used metering as a traffic management tool for two decades or more. Though metering is not a new idea in much of the United States, modern communications and computing technologies have provided ways for dramatic improvement in even the most established locations.

The purpose of ramp metering is to reduce both recurrent and nonrecurrent congestion on mainline highways and freeways. Whether implemented as a stand-alone solution or as part of a full Freeway Management System, metering has been shown in numerous deployments to be an effective tool in reducing travel times and delay.

3.2 Types of Metering Control

There are several levels of operational complexity in existing metering control algorithms. Figure 3.1 illustrates this relationship between complexity and cost for several classes of metering algorithms currently used or under development.

- *Pre-Timed Meter Control*. Pre-timed control is based on pre-set metering rates for specific times of day programmed into the field controller, identical to pre-timed traffic signal control. While its use has been well-established, pre-timed control requires voluminous historical data to support its implementation and often requires seasonal adjustments throughout the year. It is designed to mitigate only recurrent congestion (i.e., commuter traffic), and is not responsive to flow aberrations due to weather, construction, or incidents. Likewise, because rates are based on *averaged* historical data, at any given time sites will be metering either too fast or too slow for current conditions. However, for initial metering deployments, pre-timed control is an inexpensive way to provide measurable impacts and is a proven technology; the FHWA estimates that up to 90% of the operational effectiveness of ramp metering may be achieved using engineered, pre-timed control. Additionally, pre-timed control is programmed into field controllers in virtually every metering deployment worldwide as a backup metering control strategy to responsive or advanced system-wide strategies, in the event of communication or detector failure.

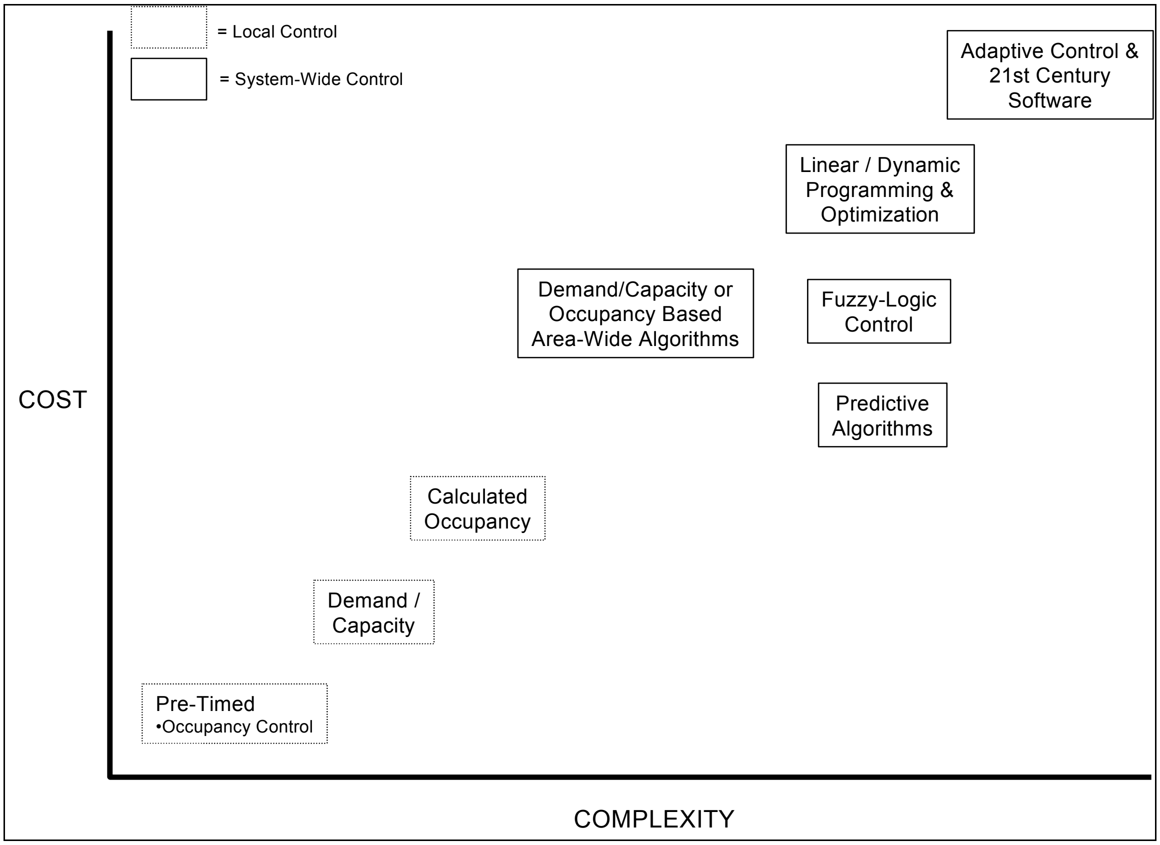

Figure **3.1 Relation between complexity and cost for metering methodologies.**

- *Local Responsive Control.* Responsive control is based on detection near the ramp—this upstream, downstream, or at the merge point—where mainline speed, volume, and occupancy are monitored. Based on these indicators, local control uses either demand-capacity or occupancy-relationship algorithms to calculate metering rates for the conditions present at each ramp. As with pre-timed control, local control is a proven strategy and is often used as a backup control method when advanced algorithms are present. While responsive to flow aberrations resulting from weather, incidents, etc., local control also has negatives in its operational theory; it requires congestion to "backup" all the way to a ramp before it can react to the conditions, and it requires the application of smoothing algorithms to prevent drastic swings in metering rates in response to variations in mainline flows. Additionally, local control requires a dedicated maintenance program to ensure detector operation.

- *Area-wide* or *Systemwide Control.* Coordinated control also uses speed, occupancy and volume indicators from the roadway to select metering rates, but does so on a system-wide basis. The mark of such a system is coordinated activity between ramp locations, accomplished either through direct field controller communication (as with the Denver Helper system) or through a central control point (as with the NET SWARM system). See the TransCore study for a general summary of these systems

(*TransCore 1999*). Different systems may base their rate calculation for any number of ramps on a detection point anywhere in the system, generally a predefined bottleneck. Likewise, they may base calculations on demand-capacity or occupancy indicators, or in the case of more advanced strategies, on optimized metering rates based in linear or dynamic programming. Frequently, these systems will calculate several metering rates based on conditions at several points within the system, then implement the most restrictive rate required at each site. Coordinated systems resolve the disadvantages of both pre-timed and local control, but generally require extensive communications infrastructure and configuration/development to implement. This infrastructure can be costly.

There are numerous algorithms in use throughout the world, each based on one of these basic principles. Most variations are a result of changes invoked by the deploying agency, and algorithms may be found that use all levels of complexity, including predictive or artificial intelligence elements meant to provide more pro-active operation.

3.3 Metering Operations

As discussed earlier, the primary purpose of ramp metering is to reduce, if not prevent entirely, congestion. Metered control addresses two of the primary causes of congestion; ramp storage and increased diversion to address a mainline volume-capacity ratio greater than 1.0, and forced gapping of onramp vehicles to address the impact of a merging or weaving section that causes turbulence.

While different strategies use different mainline flow indicators for rate calculation, experience has shown that occupancy is the most effective flow conditions indicator. Table 3.1 shows the relationship between traffic conditions, occupancy levels, and traffic density for a freeway.

Table 3.1 Relation of occupancy, density, and traffic conditions.

Condition	Occupancy (%)	Density (vpmvl)	Speed (mph)
Free-Flow	0-15	0-35	55-70
Near Capacity	15-25	35-50	50-60
Recurring Congestion (At Capacity / Saturated Flow)	25-40	50-90	40-50
Severe Congestion	>40	90-200	10-20
Stopped / Jam	>90	180-250	0-10

The effects of congestion are self-perpetuating. It has been estimated that for each minute of delay or congestion introduced into a freeway flow, an additional 4 minutes are required for the resulting "shockwave" to dissipate. Likewise, as congestion begins and vehicles slow, the capacity of the mainline facility decreases, which worsens the congestion and the process continues cyclically. The Highway Capacity Manual

(HCM 2000) estimates free-flow capacity in a freeway corridor to be 2000 to 2300 pcphpl. During congestion, however, as speeds drop, this capacity drops as well.

Agencies like MnDOT have worked out this “two-capacity” phenomenon with finely-tuned metering to increase facility capacities to more than 2400 pvphpl in some areas. Such results are important to understand because the relationship between capacity and traditional MOEs is not a linear one. Mainline storage (queuing) during a congestion period which causes a 2 to 7% reduction in roadway capacity may cause a corresponding MOE degradation of 20 to 25%.

Metering rates, expressed in vehicles-per-hour, are calculated to correspond to volume capacities found to be available on the mainline. While some strategies have an infinite metering rate selection available through variable metering rates (bounded by maximum and minimum rates), the majority of algorithms classify available capacities within a small number of bins corresponding to 5 to 6 set rates. Maximum and minimum rates of 900 vph (4-second cycle) and 240 vph (15-second cycle) respectively have been identified by both CalTrans and the 1995 Handbook of Traffic Control Systems as the effective boundaries on single-lane ramps. These values have a standard 1.5- to 2.0-second green or green plus yellow time, the remainder (variable portion) being red time. The upper limit of 900 vph is based on a minimum acceptable headway for gapping merging vehicles. The lower limit of 240 vph is based on driver surveys at existing ramp installations, where it was found that cycles longer than 15 seconds resulted in dramatic increases in meter violations.

3.4 Meter Design

Ramp meters have been installed on virtually every form of freeway entrance ramp used in the United States. Single-, double-, and even triple-lane ramps; single- and multi-lane ramps with High Occupancy Vehicle (HOV) lanes or transit bypass lanes; and ramps that are part of Single Point Urban Interchange (SPUI), Diamond, and Clover-Leaf interchanges have all been metered successfully. While not applicable in the Salt Lake City region, meters have also been successfully deployed on freeway-to-freeway connector ramps in parts of Minnesota and California. However, these applications demonstrate that only properly engineered metering placements can be effective; unique designs based on-ramp geometry are required for each meter location to ensure optimal meter operation at each site.

Two considerations generally govern the physical location of a meter on a ramp—storage capacity required at the site (based on historical volumes) and acceleration distance required (based on grade and the vehicle types using the ramp). Some agencies, such as MnDOT, require 2 lanes on a ramp prior to installing a meter, accomplished by widening the ramp or re-striping the existing lanes, as a way to ensure adequate ramp storage into the future.

The components of a metering deployment may vary based on the metering strategy used, but in general consist of the following elements, which are illustrated within a typical entrance ramp geometry in Figure 3.2.

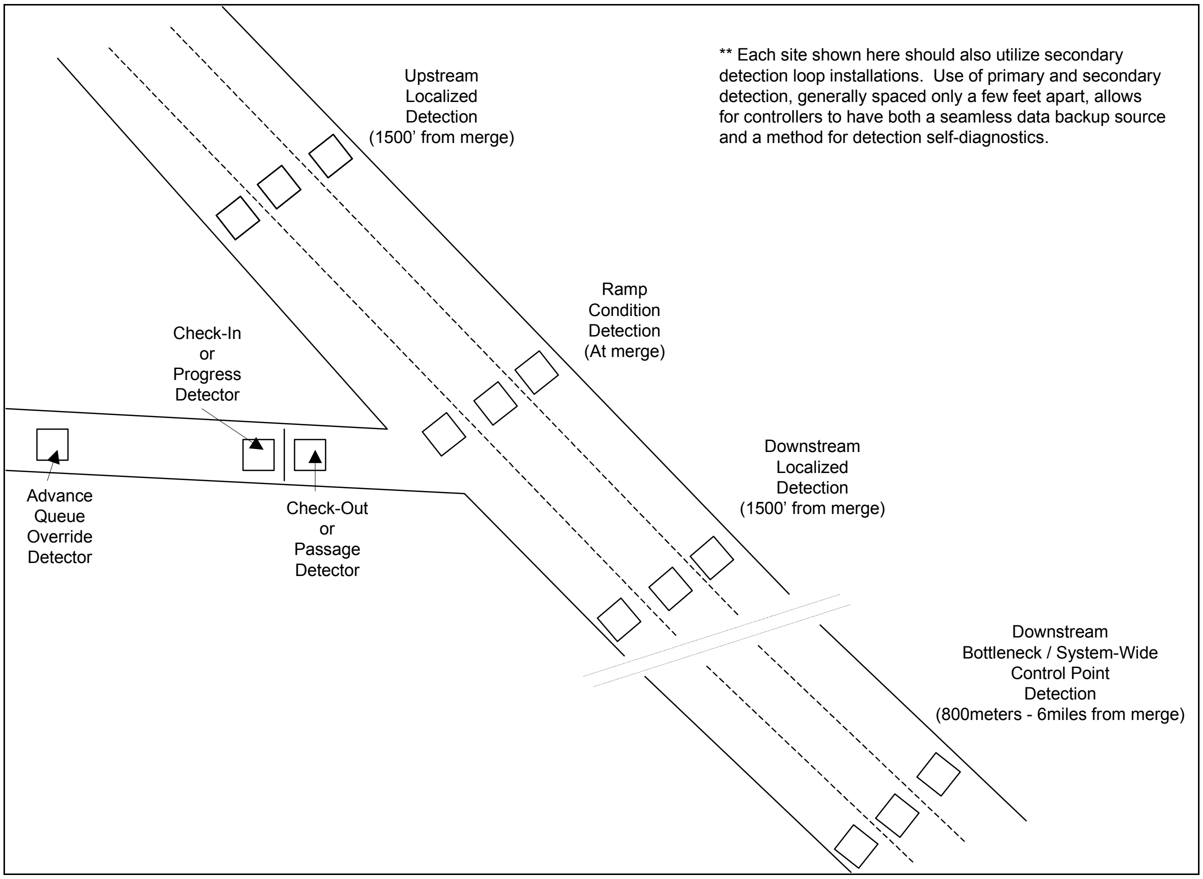

Figure **3.2 Potential detector placements for various metering strategies.**

- *Signal Head(s)*. These may be either two or three lamp signals. The MUTCD requires dual-head placement (on either side of the ramp) on multiple lane ramps.

- *Controller & Cabinet*. The modern controller standards—CalTrans Model 2070 and the NEMA TS-2—both allow for metering control. In some strategies, meter control is maintained at a central location rather than in the field, with central communication enabled through the controller.

- *Stop Bar with Presence/Passage Detection*. A stop bar is necessary next to the signal head, with both a check-in (presence) detector prior to the bar to indicate a waiting vehicle, and a check-out (passage) detector after the bar to indicate clearance of the area prior to allowing another vehicle to proceed.

- *Mainline Detection*. Depending on the metering strategy used, this may consist of no detection (pre-timed control), a single detector station (local responsive control), or multiple detectors upstream or downstream of the ramp (local and systemwide control). While any number of available detection technologies may be used successfully to support metering operations, the most popular (due to its proven reliability) remains the traditional 6 ft by 6 ft (6x6) square or circular 6 ft diameter inductive loop detector. For any strategy, detector placement is vital to correctly gauging mainline flow conditions.

- *Ramp Detection*. Queue override detection is a must for metering installations to prevent stored vehicles on the ramp from "spilling" back onto the surface streets. Determination of how best to respond to queue override detections (flush the ramp, increase the metering rate, etc.) must be a part of the metering strategy design.

- *Communication*. Necessary only in coordinated or centrally controlled systems. Mediums including twisted pair, microwave and fiber optics have all been used successfully in existing deployments. This level of installation is often reserved for metering systems being installed as part of a regional ITS deployment, where a communication infrastructure is already deployed.

4. ALGORITHM DESCRIPTIONS

The following sections detail the operation of the three algorithms selected for study as part of this project. The descriptions in the following sections were taken from TransCore's study that selected these three algorithms to be best suited for the Wasatch Front region (TransCore 1999). For more detailed, step-by-step operational descriptions and application theory for the Salt Lake City region, see the software logic defined in the appendices. Please note that the graphics used in the TransCore study were replaced with new ones to reflect the current programs.

4.1 Denver, Colorado Helper Algorithm

4.1.1 Background and experience

Ramp metering was introduced in the Denver area along the I-25 freeway in March 1981 (See Figure 4.1). The initial deployment consisted of five local traffic responsive metered ramps. This pilot project was considered successful, and additional ramp meters were installed along several freeways in the Denver area in 1984. As part of this secondary deployment, a computer control system was built to allow centralized monitoring and override control for all the metering locations.

A comprehensive evaluation of this coordinated traffic responsive system was conducted in 1988 and 1989. The results showed that if the local traffic responsive algorithm could maintain a mainline speed of 90 km/hr (about 55 mph) or more, centralized control had little or no benefit. However, when speeds were less than 90 km/hr (55 mph), centralized control was found to be very effective in reducing congestion. There have been some minor adjustments, but no major changes, in the ramp metering system and its control algorithm during the past ten years.

Thirty-one ramp meters were in operation by 1998, when it was announced that an expanded traffic operations center was being planned, which included upgrading the computer control system and communications used for metering support. However, there are no current plans to significantly modify the existing metering algorithm.

4.1.2 Algorithm description

The Denver algorithm consists of a local traffic responsive metering algorithm combined with a centralized coordinated operational override feature. The ramps being controlled are divided into six location groups (or zones), with one to seven ramp meters assigned to each group. Metering is permitted only during the weekday peak periods, freeway traffic conditions being monitored by the central computer to adjust the starting and ending of metering operation as needed.

Figure 4.1 Map of the Denver metropolitan area
(Source: http://www.mapquest.com, Accessed 5/24/2002)

Within the local responsive algorithm, each meter selects one of six available metering rates based on localized upstream mainline occupancy. Ramp presence and passage detectors are used to detect vehicles waiting and clearing the ramp signals. Ramp queue detection is also used, increasing the metering rate one level per time interval (as required) to clear excessive ramp queues. The algorithm also incorporates an exponential smoothing function to prevent wide swings in metering rates during concurrent time intervals.

At the coordinated control level, the central computer monitors and collects detector and metering data from each ramp controller every 20 seconds (metering time interval). So long as a meter is not operating at its most restrictive metering rate *and* the ramp queue detector is not exceeding its threshold occupancy value, the ramp is classified as “not critical.” If a meter is operating at its most restrictive metering rate *and/or* the ramp queue detector is exceeding its threshold occupancy value, the ramp is classified as “critical.”

When a ramp is classified as critical, the centralized algorithm immediately begins to override upstream ramp control. If a ramp remains critical for three consecutive time intervals, the central computer reduces the metering rate at the next upstream ramp by one metering rate level. If the ramp remains critical, the process moves upstream at a rate of one ramp per time interval until the problem is either remedied or all upstream ramps within the location group have been overridden. If more restrictive ramp control is still required once all ramps in the group are overridden, the metering rates at ramps in the next upstream location group(s) are then reduced. This coordinated control state continues until all ramps return to the “not critical” state, when the ramps revert to local control in the opposite order in which they were overridden, one ramp per time interval.

4.2 Minnesota Zone Algorithm

4.2.1 Background and experience

Ramp metering was introduced in the Minneapolis/St. Paul area along I-35 East in 1970. These first meters were initially controlled with time-of-day metering programming, then converted soon thereafter to local traffic responsive control. The metering system has been periodically evaluated and continues to show improvements in freeway traffic operations

By 1974, a second ramp metering system was installed along a 27-kilometer (17-mile) section of I-35 West, including 39 ramp meters, 16 closed circuit television cameras, 380 roadway detectors, and a computer control monitor at the Mn/DOT traffic management center. After ten years of operation, comprehensive evaluations showed increased freeway speeds and reduced freeway accidents and air pollution.

Over 300 additional ramp meters have been deployed between 1988 and 1995, bringing the current total to almost 400 meters in the Minneapolis/St. Paul area. Over the next five years, plans are to install meters along the remainder of the Twin Cities freeway network. (See Figure 4.2 to see the latest changes to Mn/DOT's ramp metering system.)

The keys to the success of the Twin Cities metering system are its staged implementation on a segment-by-segment and freeway-by-freeway basis over time, strict attention to bus priority and priority entry control, and freeway-to-freeway connector metering.

Author's note: The Twin Cities underwent a study to determine the effectiveness of its meters in the fall of 2000; the study concluded that the benefits in a dollar amount outweighed the cost (see Table 1.2) (Cambridge Systematics et al. 2001).

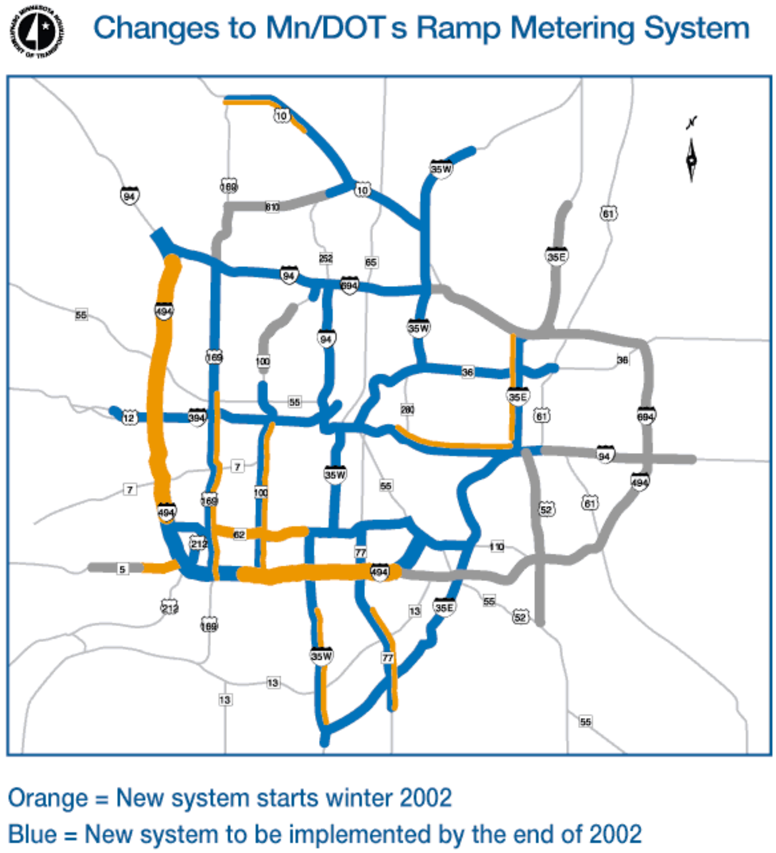

Figure 4.2 Coverage of metering program in the Twin City area.
(Source: http://www.dot.state.mn.us/rampmeterstudy/images/map011127.gif, Accessed 5/24/2002)

4.2.2 Algorithm description

The algorithm defines directional freeway facility "metering zones" as zones having variable lengths of three to six miles. The upstream end of a zone is usually a free-flow area not subject to high incident rates. The downstream end of a zone is usually a critical bottleneck, where the demand-to-capacity ratio is highest, such as lane drops, high-volume entrance ramps, and high-volume weaving sections. A zone may contain several metered entrance ramps, exit ramps, and possibly one or more unmetered entrance ramps.

The basic concept of the algorithm is to balance the volume of traffic entering and leaving each zone. All entering and exiting traffic volumes on both the mainline and the ramps are measured in 30-second increments. These total volumes are balanced to keep the density of traffic within the zone constant. Based on the density of traffic in the zone, the space available for entering traffic is calculated. The metering zone equation can be expressed as:

$$[\, A + U + M + F = X + B + S \,]$$

A =	Upstream mainline volume (measured)
U =	Sum of unmetered entrance ramp volumes (measured)
M =	Sum of metered ramp volumes (predefined)
F =	Sum of metered freeway to freeway ramp volumes (predefined)
X =	Sum of exit ramp volumes (measured)
B =	Downstream bottleneck capacity (constant—usually 2220 vphpl)
S =	Space available within the zone (computed)

Setting S equal to zero and rearranging the equation, the maximum volume that can enter the system within the zone at local and freeway-to-freeway ramps becomes:

$$[M + F = (X + B) - (A + U)]$$

Stored historical volumes are available to the system to account for detector failures in determining X, A, or U. The metering rate for each metered local and freeway-to-freeway ramp is determined from the M + F value and the individual ramp factors. These ramp factors are predefined by the system users for each metered location, defining ramp priority at each site to control the split of available metered volume. Every meter has six distinct metering rates, varying from no metering to a cycle length of 24 seconds. All green times are fixed at 1.3 seconds; all red times are fixed at 0.7 seconds.

The algorithm also incorporates occupancy detection along the roadway within each zone to account for localized congestion and queuing due to incidents, weather, construction, etc. Based on the measured occupancy at each detector site, metering rates within the zone are adjusted to account for localized traffic conditions.

4.3 Seattle, Washington Bottleneck Algorithm

4.3.1 Background and experience

Beginning in 1981, WSDOT implemented metering with the bottleneck algorithm on I-15, north of the Seattle central business district. A six-year evaluation study was then undertaken, consisting of seventeen southbound ramps during the AM peak and five northbound ramps during the PM peak along a 6.9-mile test corridor (see Figure 4.3 for Seattle's freeway network).

Over the study period, travel time dropped from 22 minutes before metering to 11.5 minutes after the implementation, despite higher traffic volumes (mainline volumes increased over 86% northbound and 62% southbound). The accident rate dropped about 39%, and average metering delays at each ramp remained at or below three minutes.

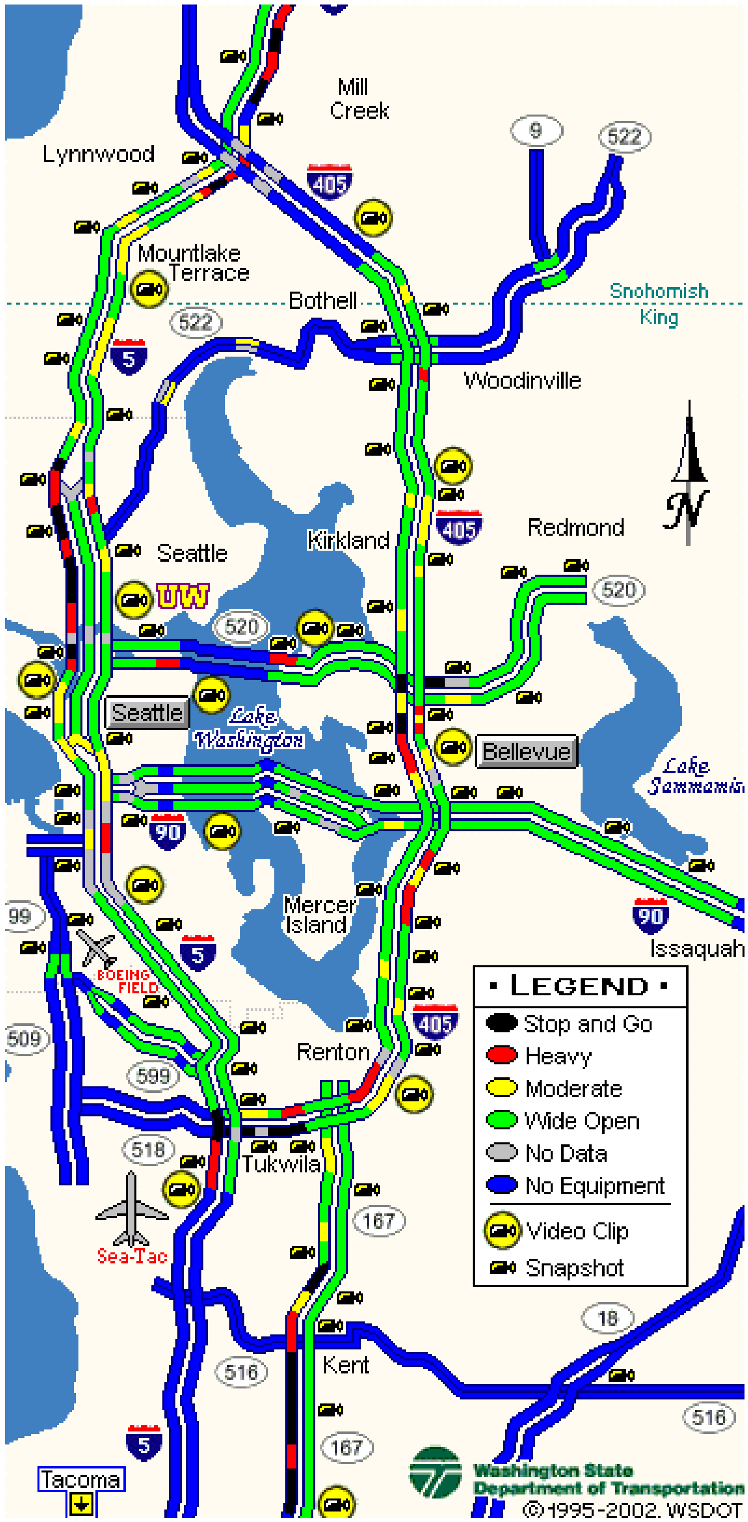

Figure 4.3 Map of the Seattle freeway network.
(Source: http://www.wsdot.wa.gov/PugetSoundTraffic/cameras/, Accessed 5/24/2002)

4.3.2 Algorithm description

The Seattle Bottleneck metering algorithm is described as one of the most sophisticated in the country due to the presence of several internal adjustments, including a volume reduction based on downstream bottlenecks and localized adjustments, such as queue override. The system currently uses local responsive detector data (upstream occupancy) at each ramp, as well as bottleneck data, to determine both a local metering rate and a bottleneck metering rate. The more restrictive of the two rates is then implemented at each ramp. (See Figure 4.4 for the operational flow chart of the Bottleneck algorithm.)

At the local level, historical data is used to determine approximate volume-occupancy relationships near capacity for each ramp location. Local metering rates are then calculated to allow ramp volumes to equal the difference between the estimated capacity and the real-time upstream volume.

The coordinated Bottleneck algorithm is activated when the following two criteria area met: (1) a downstream bottleneck-prone section surpasses a predetermined occupancy threshold, and (2) the "zone" or area of influence upstream of the bottleneck is storing vehicles. The algorithm then uses centrally assigned metering rate reductions applied to meters in the zone to reduce the number of vehicles entering the mainline by the number of vehicles stored in the bottleneck area of influence.

After selecting the more restrictive of the local and bottleneck metering rates, the algorithm further adjusts the rate based on detected and physical conditions at each site. Each ramp has both queue and advanced queue detection to prevent spillback onto the arterial street network. Metering rates are increased when the occupancy on a ramp exceeds a predetermined threshold for a specified duration, with the increase based on whether occupancy or duration is exceeded. High occupancy vehicle (HOV) adjustment accounts for the difference between the number of cars targeted for freeway entry and the actual number of cars that enter because HOV lanes are typically not metered. The same adjustment takes place to account for violators.

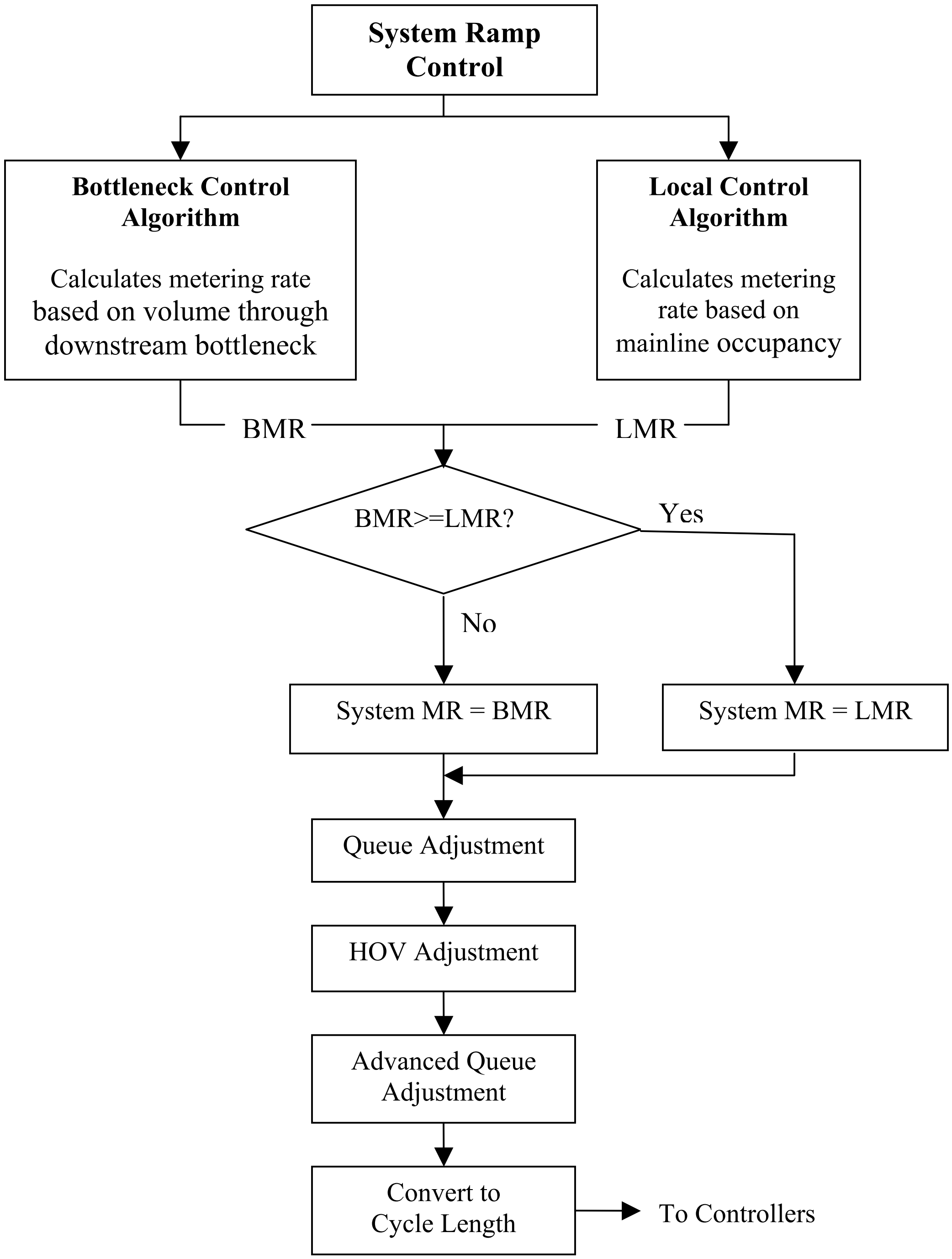

Figure 4.4 Bottleneck algorithm operational flow chart.

5. STUDY AREA DESCRIPTION

5.1 Study Location

The simulation study area is a 10-mile stretch of Interstate 15 in Davis County, Utah, between the cities of Bountiful and Farmington: from the Beck St. interchange just below the junction between I-15 and I-215 to the I-15/SR89 diverge point in Farmington (see Figure 5.1). This section was chosen because when the study began, there was much less construction activity than on the I-15 segments in central and south Salt Lake City. Also, the length of the section was ideal to test coordinated ramp metering algorithms.

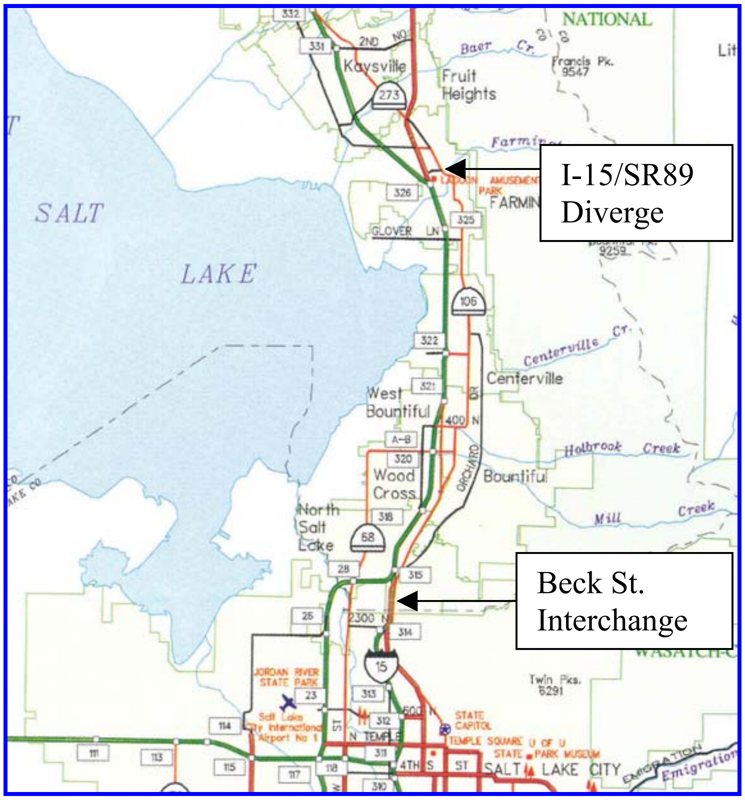

Figure 5.1 Study site. (Source: UDOT Road Map)

This section of freeway was recently widened, with the addition of new lanes in the median, expanding the roadway from 3 to 4 lanes in each direction. Before the addition of the new lanes, the following ramps were metered (from south to north):

<u>Interchange:</u>	<u>Ramp to:</u>
Beck Street	NB I-15
2600 S.	NB I-15
500 S.	NB I-15
400 N.	SB I-15
Parrish Lane	SB I-15
Glover Lane	SB I-15

Along with the expansion of the roadway, additional ramp meters were installed at the following ramps (from south to north):

Interchange	Ramp
2600 S.	SB I-15
500 S.	SB I-15
400 N.	NB I-15
Parrish Lane	NB I-15

The infrastructure needed to interlink the ramp meters with each other as well as with the central traffic operations center was placed along the corridor, allowing for the meters to be operated as part of a coordinated regional transportation system in the future, with or without the use of one of the algorithms to coordinate the meters.

5.2 Results of Travel Time Study

This section presents the results of a travel time study conducted at the study site. The objectives of the travel time study were to measure average speeds of the segments between the interchanges and to evaluate subjectively the level of service at various locations in the study area. It was also meant to identify physical bottlenecks along the freeway segment and use the information collected during the runs as a reference for "calibrating" the simulation model. During this observation the following data were collected:

- Times (hour and minute) using the clock in the dashboard of the vehicle when the probe car passes the check points
- Travel speed as shown in the speedometer of the vehicle
- Level of service (LOS) by subjective judgment

The sample photos of level of service for basic freeway segments (see Figure 5.2) presented in the Highway Capacity Manual 2000 (TRB 2000) were used as a guide as we evaluated the level of service subjectively. The checkpoints used for this travel time study are in Table 5.1.

Table 5.1 Travel time checkpoints.

NB	SB
Exit: Gore point of I-15 and Farmington off-ramp	Entry: Ramp metering stop line on SB Farmington on-ramp
Parrish Ln.	Parrish Ln.
400 N.	400 N.
500 S.	500 S.
2600 S.	2600 S.
Entry: Merge point of I-15 and the Beck St. on-ramp	Exit: Gore point of I-15 and US-89
Length = 10.3 miles	Length = 9.4 miles

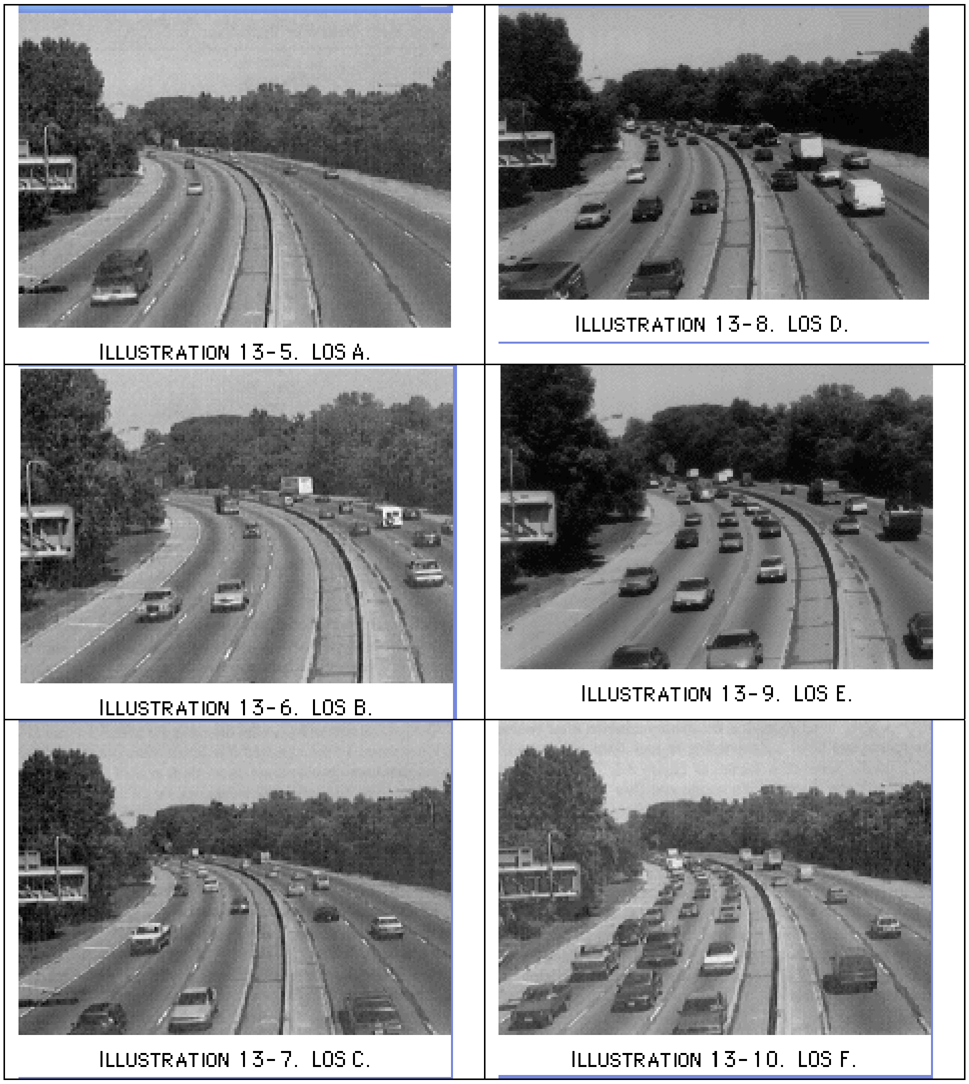

Figure 5.2 Level of service for basic freeway segments.
(Source: HCM 2000)

5.2.1 Evening peak period

Evening traffic was observed between 3:44 PM and 6:25 PM on January 3, 2001, on the studied freeway section. The weather was fine, but there was a slight fog in the area, and the fog warning sign with flashing lights located between 400W and 2300N ramps was on. However, it appeared that the fog was not thick enough to cause the drivers to slow down in the studied section of I-15.

Table 5.2 presents a summary of the travel time study conducted during the evening peak hours. It seemed the southbound (SB) direction had consistent demand throughout the observation period. The northbound (NB) direction seemed to have its peak demand between 4:30 and 5:30 PM. There was no stop-and-go situation at any segments of the observed section during the studied period. The only exception was a short period of slow down, from approximately 60 mph to 30 or 40 mph, just south of the NB 500 South off-ramp for about 1 mile. Since the curb lane was occupied by very slow vehicles trying to get off at this ramp, only 3 lanes were available for through vehicles. The LOS of this section seemed either D or E during the peak period. Otherwise the NB direction traffic flowed smoothly. This NB off-ramp is the off-ramp for Bountiful residents. It is recommend that the 500 South off-ramp be given 2 lanes, just like 2600 S. An additional off-ramp lane and proper signalization at the end of the ramp will be likely to remove congestion just south of the 500 South off-ramp and provide smooth driving throughout the study freeway section.

5.2.2 Morning peak period

Morning traffic was observed from 6:01 AM to 9:08 AM, January 4, 2001. It was dark and foggy till about 7:30 AM, vehicles were traveling at about 65 to 70 mph. As shown in Table 5.3, the real peak hour appeared to be between 7:00 AM and 8:00 AM. Our initial expectation was that the two-lane section in the SB direction just south of the I-215 diversion would be congested, but this location was not congested. Some drivers exit to Beck St. SB off-ramp but they again get on I-15 from the on-ramp about one-half mile south of this diversion point. It may be that many who want to go south of Salt Lake City avoid using I-15 because the downtown section of I-15 is still under construction. During this 3-hour field observation period, Level of Service E was observed nowhere in the studied segment. There was no queue from the signalized intersections at the bottom of the off-ramps that might have blocked the main flow in the SB direction.

The results of the field observations rendered positive results in regards to finding the approximate peaks for both the AM and PM periods as expressed in the previous sections. Approximate traveling speeds and LOS were also found in Table 5.2 and Table 5.3 as a result of the field observations performed. Having found this information a simulation study methodology can be formed and a calibration of the simulation model can be checked to its validity.

Table 5.2 Evening peak travel time study summary (Wednesday, 3 January, 2001, 3:44 PM – 6:25 PM).

	NB	SB	NB	SB	NB	SB	NB	SB	NB
Exit (NB)/Entry (SB)	3:54	3:59	4:27	4:32	5:01	5:25	5:53	5:57	6:25
Parrish Lane	3:51	4:02	4:24	4:34	4:58	5:28	5:50	5:59	6:22
400 N.	3:50	4:04	4:23	4:36	4:56	5:30	5:48	6:01	6:20
500 S.	3:49	4:04	4:22	4:37	4:55	5:30	5:47	6:02	6:20
2600 S.	3:47	4:06	4:21	4:38	4:53	5:31	5:46	6:04	6:18
Entry (NB)/Exit (SB)	3:44	4:08	4:18	4:40	4:50	5:33	5:42	6:06	6:15
Approx. total travel time (min)	10±0.5	9±0.5	9±0.5	8±0.5	11±0.5	8±0.5	11±0.5	9±0.5	10±0.5
Approx. travel speed (mph)	59 to 65 mph	59 to 66 mph	66 to 72 mph	66 to 75 mph	54 to 59 mph	66 to 75 mph	54 to 59 mph	59 to 66 mph	59 to 65 mph
Comments on LOS (subjective)	Just before Beck St. on-ramp on the curve, LOS is D. In the study section, it looked C/D.	Throughout the section LOS seemed C/D.	Just like the first NB run: overall C/D. Noticed the sustained upslope in NB after Parrish Ln. There LOS seemed D.	Just like the first SB run: overall LOS seemed C/D.	Started congested. LOS seemed like D/E between 2600 S. and 500 S. LOS in the other part is more like D/C.	Just like the second SB run. Overall LOS seemed C/D.	Overall LOS seemed C/D.	Overall LOS seemed C/D.	Overall LOS seemed C.
Other comments	Smooth drive; no major congestion along the section.	Smooth drive; no major congestion observed. Many vehicles get off to I-215 and LOS on I-15 south of the exit at gore is A/B despite only two lanes.	Smooth drive. Not much slow-down at any point of the section.	Observed there was a long queue from 500 S. NB off-ramp (4:37 PM).	About 1 mile north of 2600 S. congestion caused by vehicles exiting at 500 S. seen. The curb lane was used by slow exiting vehicles as well as the off-ramp auxiliary lane. The signal at the end of the ramp seemed to be the cause.	Smooth SB drive. At 5:31, the queue near NB 500 S. off-ramp has gone. An accident clean-up was going on at the intersection to SB 2600 S. on-ramp (5:31).	Fairly smooth NB drive. No queues seen at any NB off-ramps.	Smooth SB drive. No queue was seen at any NB off-ramps. The accident clean-up was still going on at 6:00 PM.	Smooth NB drive. The ramp meter at NB Beck St. on-ramp was on. There was a short queue at the ramp meter. It looked as if the peak had passed by this time.

NB = 10.3 miles; SB = 9.4 miles

Table 5.3 Morning peak travel time study summary (Thursday, 4 January, 2001, 6:01 AM – 9:08 AM).

	SB	NB	SB	NB	SB	NB	SB	NB	SB	NB	SB
Exit (NB)/Entry (SB)	6:01	6:28	6:32	7:00	7:04	7:33	7:37	8:05	8:29	8:55	8:59
Parrish Lane	6:04	6:26	6:35	6:57	7:07	7:30	7:40	8:02	8:32	8:52	9:02
400 N.	6:06	6:24	6:37	6:55	7:09	7:28	7:42	8:00	8:34	8:50	9:04
500 S.	6:07	6:23	6:38	6:54	7:10	7:28	7:43	7:59	8:34	8:50	9:04
2600 S.	6:08	6:22	6:39	6:53	7:11	7:26	7:44	7:58	8:36	8:48	9:06
Entry (NB)/Exit (SB)	6:10	6:19	6:41	6:50	7:13	7:23	7:46	7:55	8:38	8:46	9:08
Approx. total travel time (min)	9±0.5	9±0.5	9±0.5	10±0.5	9±0.5	10±0.5	9±0.5	10±0.5	9±0.5	9±0.5	9±0.5
Approx. travel speed (mph)	59 to 66 mph	66 to 72 mph	59 to 66 mph	59 to 65 mph	59 to 66 mph	59 to 65 mph	59 to 66 mph	59 to 65 mph	59 to 66 mph	66 to 72 mph	59 to 66 mph
Comments on LOS (subjective)	LOS seemed B/C. Early but more traffic in SB than in NB.	LOS seemed A except between 2600 S. and 400 N. where it looked more like A/B.	Traffic increased. LOS seemed like C/D throughout.	LOS looked like B throughout.	LOS seemed like D but not E.	LOS seemed like B to B/C from the entry to 400 N. Then was like C beyond.	LOS was like C/D between the entry and Parrish, then D to I-215 then C/D.	LOS was like A/B at the entry, then B as I traveled north.	LOS was like C (4 lanes) throughout but near I-215 junction, B because of 5 lanes.	LOS A near the entry, then B north of I-215 junction, then was like C north of Parrish Ln.	LOS seemed like B/C north of Parrich, then B.
Other comments	Dark and foggy throughout. Snow near Parrish Ln.	Very light traffic. Foggy weather throughout.	Snowy between Parrish Ln. and 400 N.	Snow before the entry point. Wet pavement between 400 N and Parrish Ln.	Traffic notably increased. Foggy but no snow at any point in the observed section.	About 7:28AM, dawn. Notably brighter. Still foggy throughout.	Foggy throughout. No metering was on.	There was an accident between 7:40 and 8:02 AM just north of Parrish Lane. A long queue reached about 1/3 mile south of the exit. By 8:11 the accident was cleared and traffic seemed smooth.	Very foggy. But comfortably drive at 70 mph. Seemed as if the real peak were over by this time. Traffic was much lighter.	Still foggy throughout.	Traffic became much lighter.

6. SIMULATION STUDY METHODOLOGY

The objective of the simulation study is to evaluate the effectiveness of various ramp metering methods against the no-metering case in reducing congestion. This chapter discusses the cases and hypotheses tested in the simulation study, the future volume estimation procedure for sensitivity analysis purposes, the measures of effectiveness used for simulation analyses, and the direction for cost-effective comparison.

6.1 Cases and Hypotheses Tested

In total, ten WATSim simulation models were created to represent the ten cases we evaluated—5 cases each for the morning and evening peak periods. The morning peak period was defined as 6:00 AM to 9:00 PM; the evening peak period was defined as 3:00 PM to 6:00 PM. According to the field observations and volume data available for the study, the morning peak hour was between 7:45 AM and 8:45 AM and the evening peak hour was between 4:45 PM and 5:45 PM. The real peaking currently takes place for about 30 minutes or less in this segment of I-15. The five cases simulated are the following:

- No metering
- Local responsive metering (the local responsive metering portion of the Denver algorithm was used to represent the local responsive metering for the Wasatch Front)
- Denver Helper algorithm (see Appendix A for details)
- Minnesota Zone algorithm (see Appendix B for details)
- Seattle Bottleneck algorithm (see Appendix C for details)

Using these 5 cases we tested the following hypotheses:

- Local metering will not improve the operation of the freeway over the no-metering case.
- Coordinated ramp metering algorithms will not improve the operation of the freeway over the no-metering case.
- Coordinated ramp metering algorithms will not improve the operation of the freeway over local responsive metering.
- Three coordinated metering algorithms will yield results that show no statistically significant difference in the selected measures of effectiveness among them.

Because we tested three coordinated ramp metering algorithms we have the following combinations of tests.

Table 6.1 Comparisons of cases.

Null Hypothesis Number	Combination of Cases
1	No metering vs. Local responsive metering
2	No metering vs. Denver algorithm, No metering vs. Seattle algorithm, No metering vs. Minnesota algorithm
3	Local responsive metering vs. Denver algorithm, Local responsive metering vs. Seattle algorithm, Local responsive metering vs. Minnesota algorithm
4	Denver algorithm vs. Seattle algorithm, Denver algorithm vs. Minnesota algorithm, Seattle algorithm vs. Minnesota algorithm

6.2 Estimating Traffic Demand Increase in the Future

To evaluate the performance of ramp metering methods in future years, it is necessary to make estimates on future traffic demand at the study site. At first, the future demands estimated by a regional transportation demand model were examined. Unfortunately the traffic simulation model requires detailed turning volume data, but the regional transportation demand model is not meant for detailed operational analyses. For instance, at some intersections in the study area the output from the regional model showed unrealistic turning volumes (such as zero turning vehicles where turning vehicles do exist). Therefore, we abandoned the idea of using volume data taken from the regional transportation demand models.

Although it is not ideal, another method of estimating future traffic demand that could be used for the study was to extrapolate from the previous traffic demands in the study area. Table 6.2 and Figure 6.1 show AADTs (Annual Average Daily Traffic) on I-15 near the interchanges in the study area. This table and figure show that the traffic demand in the study area rapidly increased between 1995 and 2000 despite the I-15 reconstruction work that was underway during this period. The sections between the junction of I-215/I-15 and 400 North in West Bountiful have experienced particularly dramatic increases in traffic demand, a possible reflection of the population growth in the area. The 10% reduction near the Beck Street interchange seems to be a result of the I-15 reconstruction work. It is likely that drivers avoided the construction work in downtown Salt Lake City and used I-215 as a detour to get to the south of the city. It is hard to say whether the study area will continue to have this high growth pattern; however, it is safe to say that the study section will experience an increase in traffic volume of approximately 10% in five years and 20% in ten years.

Table 6.2 AADTs in the study area.

Location Identifier (South to North)	1994	1995	1996	1997	1998	1999	2000	Change between 1995-2000
Beck St.	109,235	110,930	112,760	102,495	93,577	91,237	99,770	-10%
Junction I-215	117,855	119,685	121,655	124,926	139,935	147,527	160,804	34%
2600 South	103,285	104,890	106,620	109,178	120,095	126,099	137,890	31%
500 South	95,000	96,475	98,065	100,418	109,455	112,738	123,280	28%
400 North	82,000	83,275	84,650	86,596	93,090	98,187	104,034	25%
Parrish Lane	96,290	101,835	103,300	105,400	112,705	112,870	115,125	13%
Grover Lane	87,565	92,610	93,945	95,855	102,500	102,650	104,700	13%

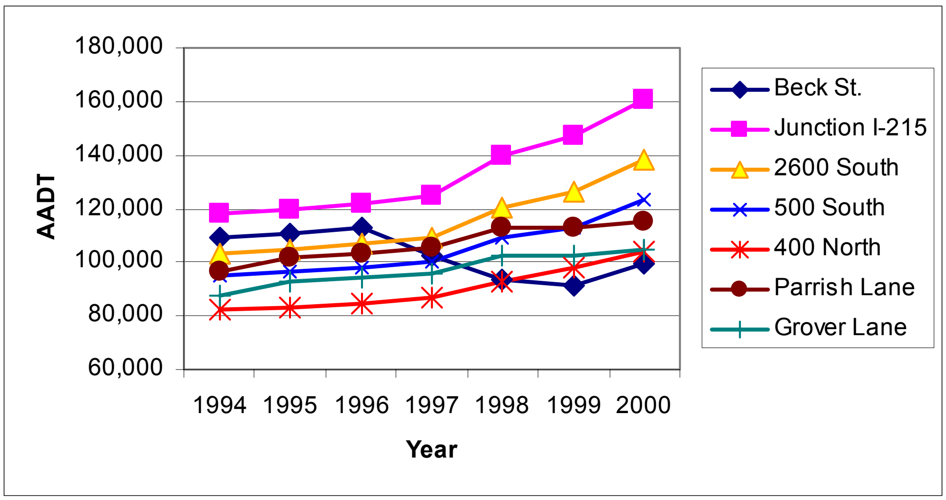

Figure 6.1 Changes in AADT between 1994-2000 in the study area.

Another method of estimating traffic demand in the study area is to check the estimated population growth in the areas surrounding this section of I-15. Table 6.3 shows the population growth history for the three counties taken from Perlic's report (Perlic 2000). The average annual population growth in the three counties is about 2%. We thus assume that traffic growth will follow a similar trend. Thus, traffic will increase by 20% in 10 years and about 50% in 20 years, assuming the annual traffic growth will be compounded.

Table 6.3 Population growth of the four Wasatch Front counties

County	1970s	1980s	1990s (1990-1995)
Weber	1.4%	0.9%	1.9%
Davis	4.0%	2.4%	2.8%
Salt Lake	3.1%	1.5%	2.1%

Source: Perlich, Pam. *Demographic and Economic Analysis.* Chapter 1: Population Growth in Utah 1970-1995. http://www.governor.state.ut.us/dea/publications/utah90s/chapter1.htm

Since a commuter rail and a new highway (i.e., Legacy Highway) are expected to be in place in the study area within 20 years, it is somewhat of an overestimation to assume a 50% increase for the study area. Therefore, we conclude that the traffic in this segment of I-15 would increase by 40% within 20 years. This is purely an educated guess, but these values can be used to evaluate whether sophisticated coordinated metering programs would provide benefits over local responsive metering, or whether the current corridor capacity would not be able to handle the traffic growth in the study area if the current geometry did not change.

Based on the above discussions of traffic growth, the following three volume levels were used for this sensitivity analysis:

- Base year volume (year 1998)
- 20% increase in volume (reflecting the volume in about 2010)
- 40% increase in volume (reflecting the volume in about 2020)

6.3 Simulation Runs and Measures of Effectiveness for Comparison

For the simulation analysis, five measures of effectiveness (MOEs) were examined: volume, density, speed, travel time and fuel use. Volume, speed and density (converted to the level of service) were used for the "calibration" of the base year volume models by comparing them with the volume data provided by UDOT and the speed and density observed during field observations. Speed was not, however, used for comparing the performance of the tested ramp metering methods because speed was fairly insensitive to density increase until traffic volume reaches near capacity and because the other two MOEs, travel time and density, can adequately reflect the changes in the performance. Density is an indicator of congestion and traffic flow stability, and travel time and fuel use can be converted into monetary values.

Multiple runs of the models are necessary for simulation analysis. First, ten runs were made for each case with the base year volume to get average measure of effectiveness (MOEs) values and to "calibrate" the simulation models. The simulation results from these ten runs were fairly stable with different random number seeds; therefore, subsequent runs with increased volumes were run three times to evaluate the hypotheses set up for the analysis. The set of random numbers used for the three simulation runs were the same for each case in order to provide similar traffic flow characteristics.

The results of the analyzed cases were compared with the same volume levels using three MOEs—density, travel time and fuel consumption. The simulation models contained a few surface street intersections (see Figure D.1 in Appendix D), but only the MOEs of the freeway segments were compared to avoid biases that may be caused by the performance of surface streets. For instance, if the signalized intersections on the surface street network "fail" with increased volumes, the surface street congestion could skew the evaluation of freeway performance. After these comparisons were made, travel time values for on-ramp links that feed the ramp meters were compared to see if vehicles waiting to be served at the ramp meters experienced an inordinate amount of delay.

6.4 Analysis of Cost-Effectiveness

One important question that UDOT had as the study began was whether or not it would be cost-effective for UDOT to implement a sophisticated coordinated ramp metering method. Although the cost of installing a coordinated ramp metering system was not available and such an estimation task was outside of the scope of the study, it was possible to estimate the savings in user costs for each of the ramp metering methods compared to the no-meter case. This was done by assuming an average hourly wage for the drivers who use the study section of the freeway.

Other benefits, however, are more difficult to analyze in terms of monetary values. For instance, it is believed that ramp metering reduces accident potential in merge areas because the entry of vehicles into the main flow is regulated and can take place more smoothly. However, because accident data for coordinated ramp metering have not been accumulated, it is impossible to evaluate changes in accident rates and to convert the changes to monetary values. Instead, the change in density in the merge area was chosen as a surrogate MOE for the impact of ramp metering on safety. Qualitative discussions will be provided for these effects.

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7. RESULTS OF SIMULATION ANALYSIS

7.1 Organization of This Chapter

This chapter presents the results of the simulation analysis. First the calibration of the model is described together with the analysis of the 1998 traffic volume (base year traffic volume). This is done because these two analyses go hand in hand. For calibration, traffic volume, density and speed were used together with the data collected during the field observations. This analysis is followed by the results of a sensitivity analysis in terms of two different traffic volume levels. In the sensitivity analysis the base year volume was increased by 20% and 40% to see how the network might react to such volume increases (see Chapter 6 for the procedure used to determine these volume increase values and Appendix D, E and F for simulation model preparation process, software preparation and software input routine.).

After the results of the sensitivity analysis results of the travel time comparison are discussed. Travel times resulted for the different cases (see Table 6.1) are compared for peak one hour, peak 15-minute periods and congested links. The two latter analyses demonstrate that travel time savings achieved by ramp metering may be masked when aggregate temporal and spatial analyses were made. Since the study site had practically one really congested segment that could be effectively controlled by on-ramp metering, the savings in travel time made for that congested segment was averaged out temporally and spatially, resulting in smaller than expected travel time savings for the study section of I-15 and for the peak one hour.

After the discussion of travel time saving, results of the fuel consumption analysis and the travel time analysis for metered on-ramps are presented. All metering methods tested behaved differently, but it became apparent that travel time on metered on-ramp links increased substantially compared to the no-metering case.

7.2 Calibration of the Model (1998 Base Year Traffic Volume)

To calibrate the base year models the AM and PM peak hour volumes estimated from the annual average daily traffic (AADT) volumes for the year 1998 supplied by the Utah Department of Transportation were used. In 1998, the total AADT volume north of the I-215 and I-15 junction in Davis County was given as 139,935 vehicles (UDOT 1998a). Since the AADT was given as the total volume for both directions, a 50/50 split was assumed to represent the traffic volume of 69,967 vehicles per day in each direction. To obtain the peak hour volume in each direction, a k-factor was needed. The k-factor is the proportion of daily traffic occurring during the peak hour, expressed as a decimal (Mcshane, Roess & Prassas 1998). The k-factors that are typically used for urban highways are in the range of 0.8 to 0.10 (Mcshane, Roess & Prassas 1998). For example, the AM peak hour volume in the southbound direction was estimated to be 6,968 veh/hour (10% of 69,967 veh/day).

Approximately 6,968 vph should then be observed north of the I-215 and I-15 junction in Davis County in the base year volume AM simulation model. In Figure 7.1, we see that about 7,000 vehicles were observed during the AM peak hour on average in the ten AM base case simulation runs. Similarly, the PM base case simulation runs had a reasonable peak volume of approximately 5,250 vph (see Figure 7.2). It is typical that the PM peak period is longer and less pointed than the AM peak hour. This value is close to about 8% of the AADT. With these traffic levels observed in the simulation models, we concluded that the models are valid for further analyses to compare the effects of the different ramp metering methods considered in this study.

7.2.1 Simulated traffic volumes on the freeway

This section provides simulated link volumes from the north end to the south end of the studied freeway segment. The street names in Figures 7.1 and 7.2 show approximate locations of the interchanges that cross these streets. Note that only the southbound direction was analyzed for the AM peak hour and the northbound direction for the PM peak hour because they are the directions that experience congestion during the AM and PM peak periods, respectively.

7.2.1.1 AM peak hour

Figure 7.1 was created from the results of ten simulation runs performed. It shows the average number of vehicles per hour during the AM peak hour between 7:45 AM and 8:45 AM.

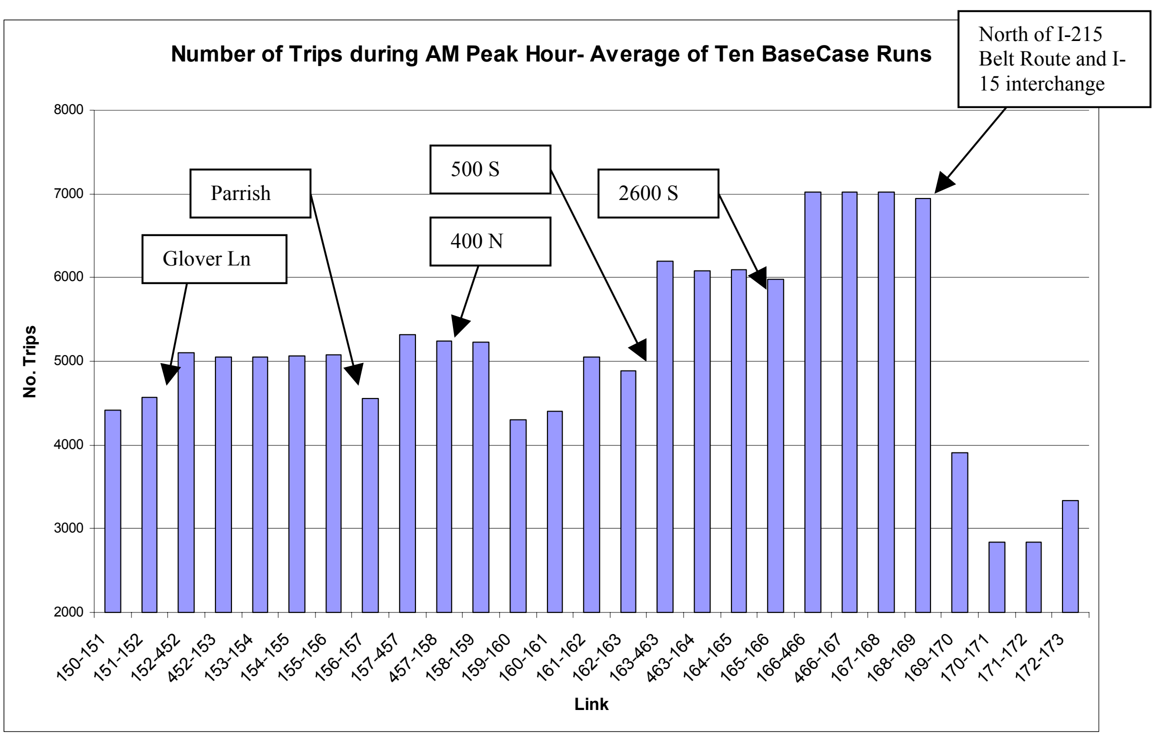

Figure 7.1 AM peak hour volumes along the studied freeway section between 7:45 AM and 8:45 AM (base year volume).

As the figure shows, an hourly volume of approximately 7,000 vehicles was observed in the simulation model during the peak hour just north of the I-215 and I-15 junction and south of 2600 South.

7.2.1.2 PM peak hour

Figure 7.2 shows hourly volumes on each link in the northbound direction of the studied section of I-15. The volumes shown are obtained in the same manner as the volumes for the AM peak period; they are the average number of vehicles obtained from ten simulation runs. The same random numbers used for the ten runs of the AM peak hour were used for the PM peak hour to make the results consistent with the AM peak hour.

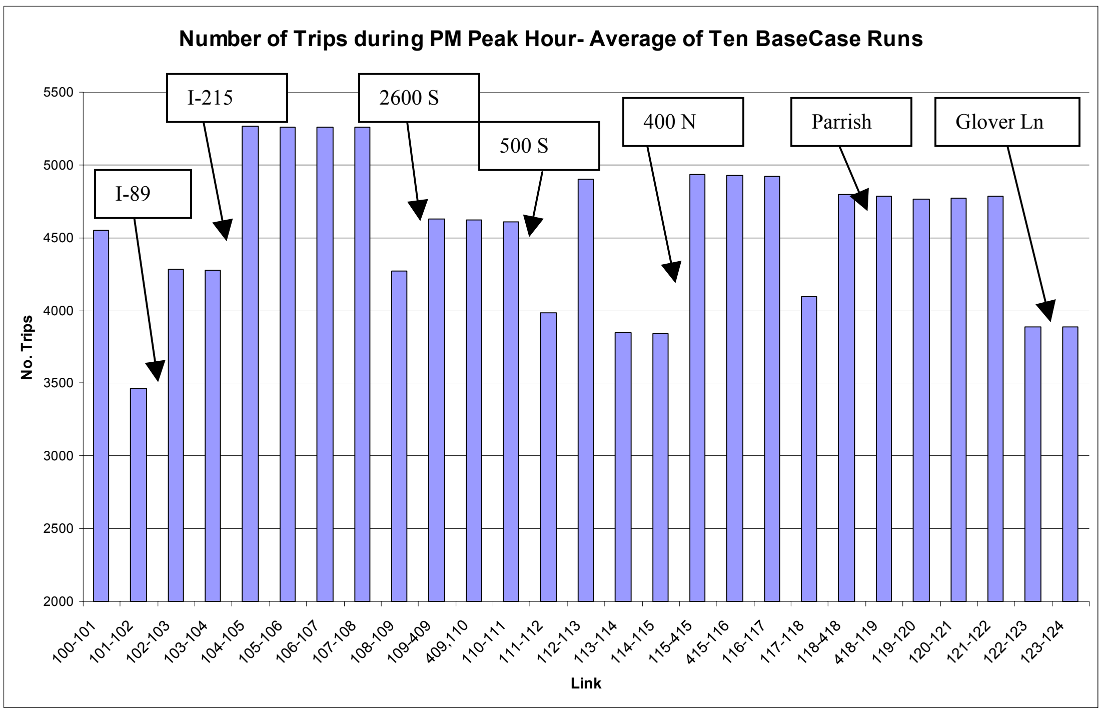

Figure 7.2 PM peak hour volumes along the studied freeway section between 4:45 PM and 5:45 PM (base year volume).

The average of ten simulation runs, as seen in Figure 7.2, resulted in a volume of approximately 5,250 vehicles during the PM peak hour between just north of the I-215 and I-15 junction and south of 2600 South.

7.2.2 Density profile along the freeway

Density profiles were used to compare the performance of the local responsive and coordinated systems against the no-metering case. The WATSim© simulation software provided an output file that contained the density values for each 15-minute time slot for the three-hour study period. Since the freeway performance was the initial focus of the study, only those density values pertaining to the freeway segment were obtained for comparison. Observations of simulation animations showed that ramps would not experience congestion at the base year volume level.

Once the density values for the peak hours were chosen for each of the no-metering and metering cases, the comparison of each case was made. To compare densities, a level of service (LOS) concept was used. The level of service characterizes the operating conditions on the facility in terms of traffic performance measures such as speed and travel time, freedom to maneuver, traffic interruptions, and comfort and convenience (AASHTO 2000). The levels of service range from level A (least congested) to level F (most congested). For the purpose of this study, the LOS criteria defined by the *Highway Capacity Manual 2000* (TRB 2000) were used. The subsequent sections illustrate the comparisons of density profiles and total travel times for the AM and PM peak hours. The AM peak hour for this simulation was between 7:45 AM and 8:45 AM; the PM peak hour was between 4:45 PM and 5:45 PM.

7.2.2.1 AM peak hour

Figures 7.3a through 7.3d illustrate the density profiles along the section of I-15 included in the study at 15-minute intervals during the AM peak hour from 7:45 AM to 8:45 AM. The figures also indicate the upper boundaries of the levels of service; for instance the level of service is D between the lines labeled C and D.

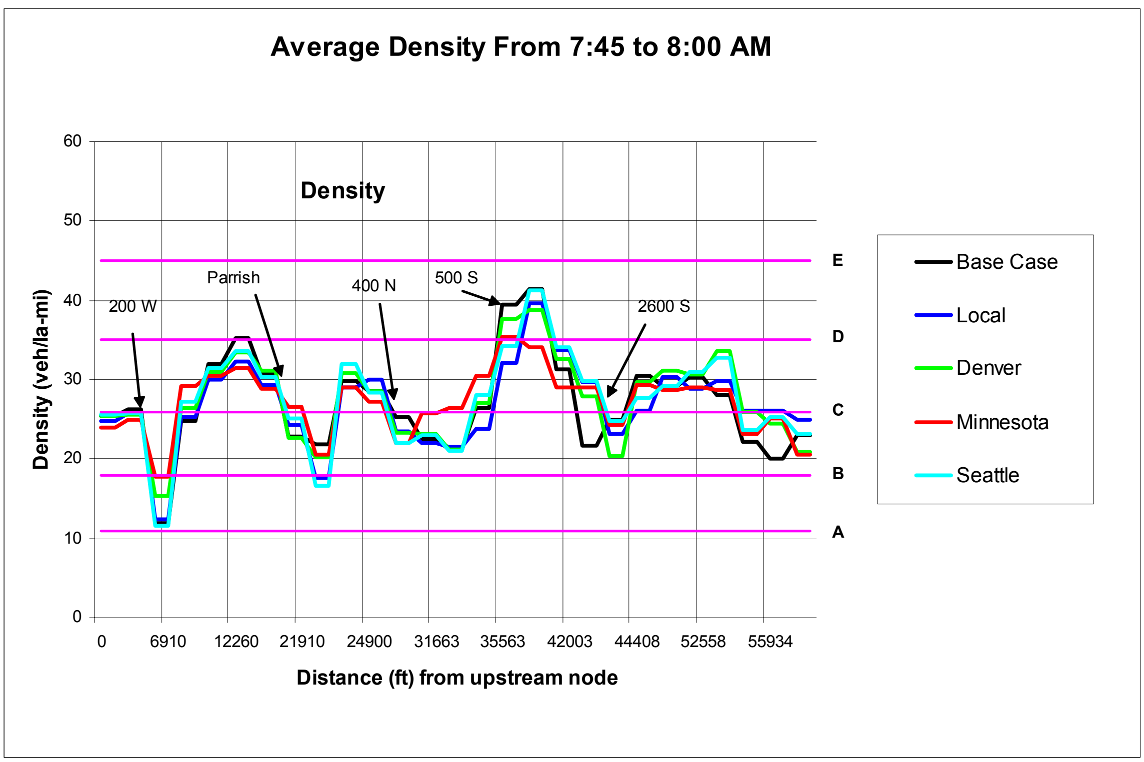

Figure 7.3a Average density profile for 7:45 AM to 8:00 AM (base year volume).

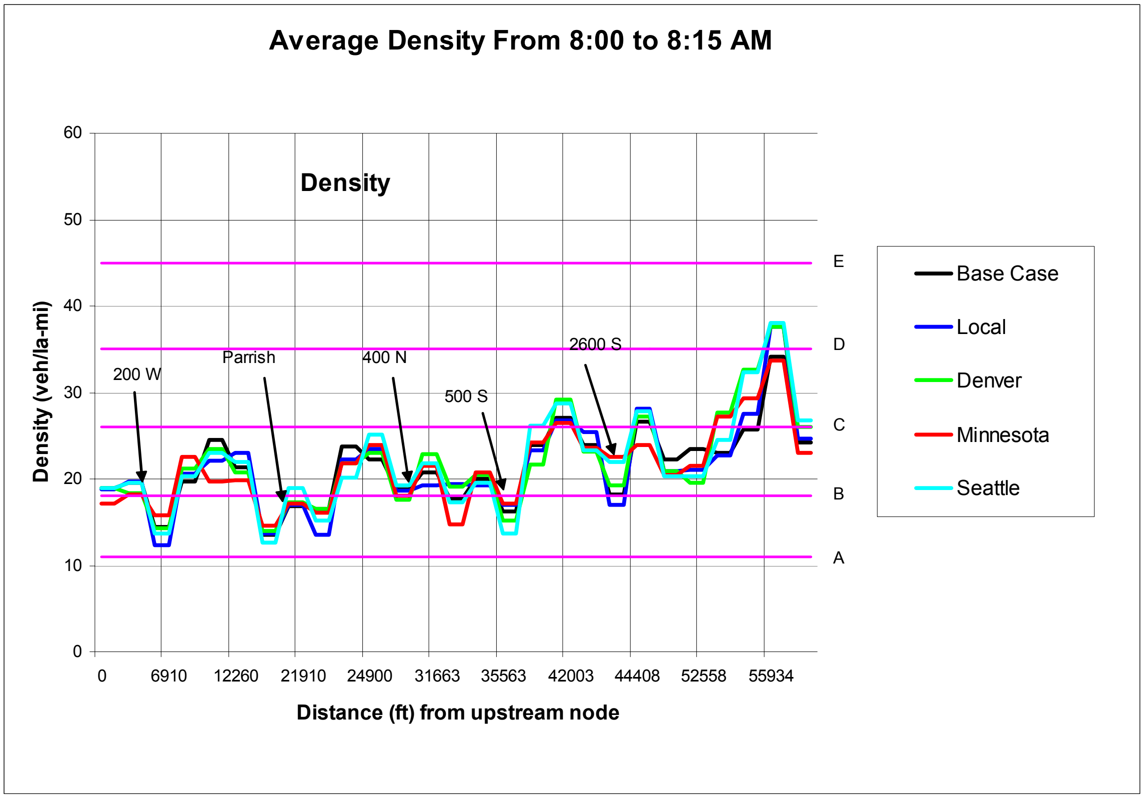

Figure 7.3b Average density profile for 8:00 AM to 8:15 AM (base year volume).

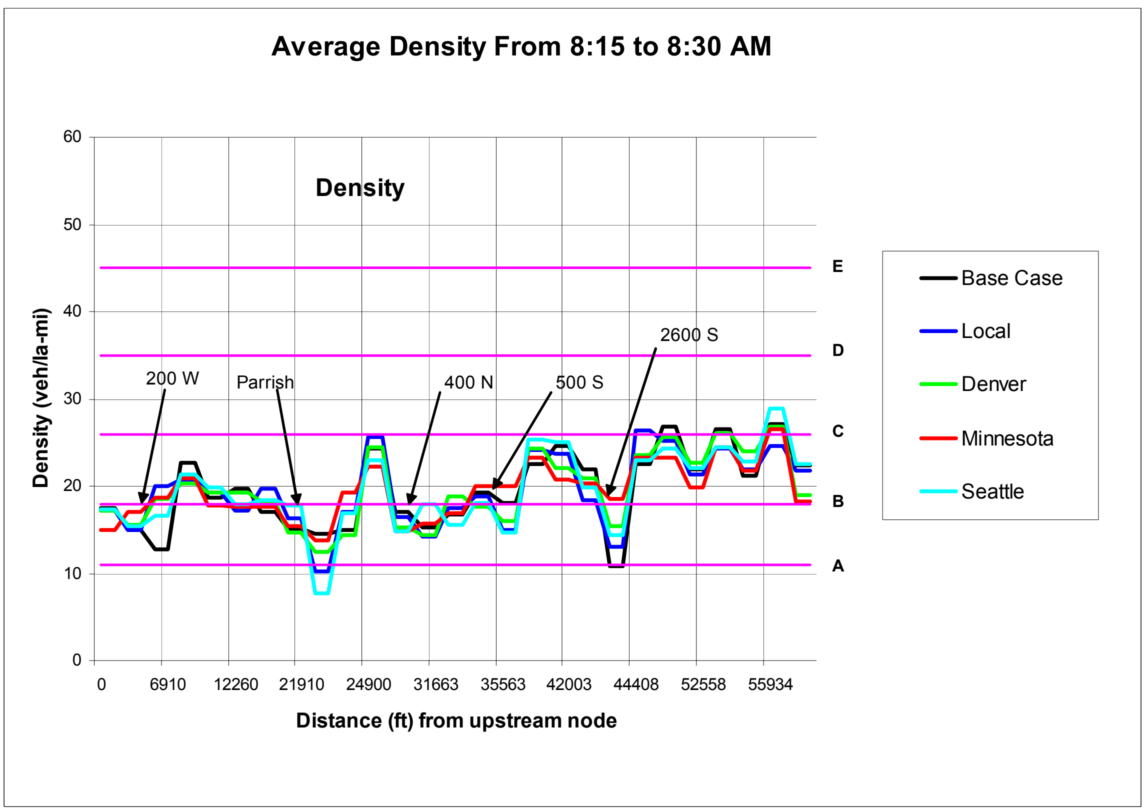

Figure 7.3c Average density profile for 8:15 AM to 8:30 AM (base year volume).

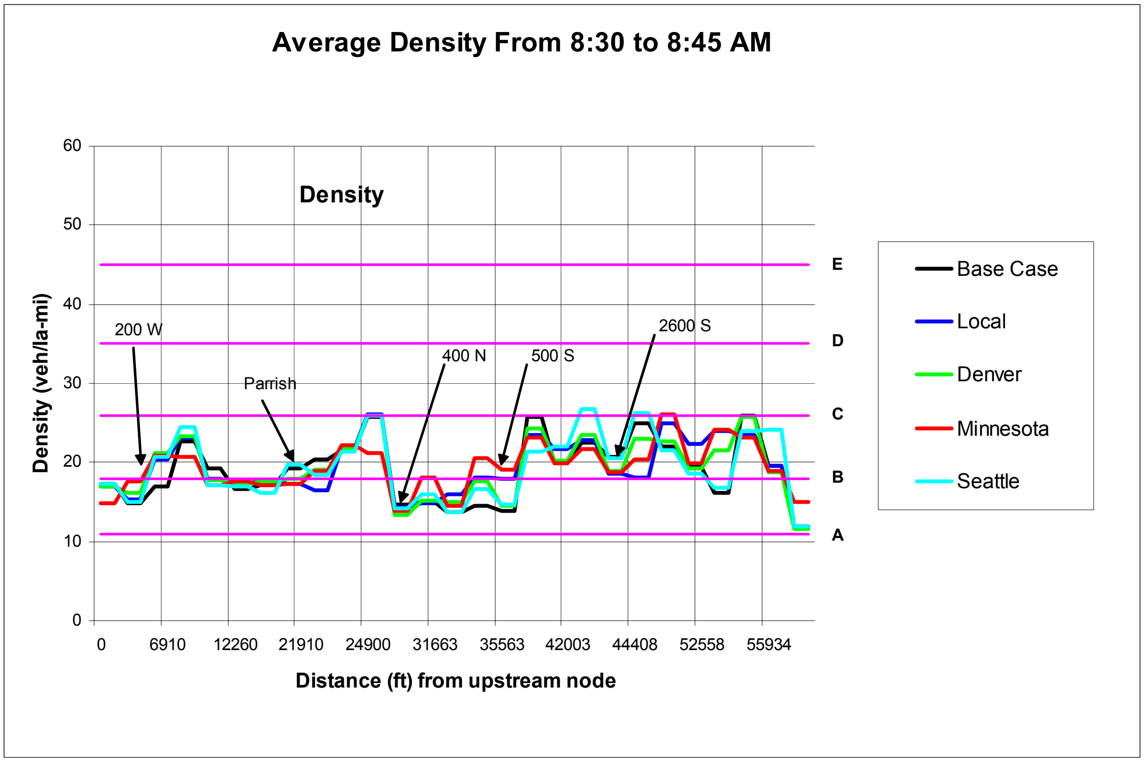

Figure 7.3d Average density profile for 8:30 AM to 8:45 AM (base year volume).

Simulations conducted with the base year volume for the AM peak hour, as seen in Figures 7.3a through 7.3d, show that the density profiles of the local responsive and coordinated systems follow a similar general pattern as that of the no-metering case. Although the local responsive at some points performed slightly better than the other cases its density profile was similar (as shown in Figure 7.3b). The level of service on the freeway on average was at LOS C. Some occasional peaks entered in the LOS D and LOS E range, but overall LOS C was observed. This result is consistent with the result of field observations, as described in Chapter 5.

The average total travel time (ATTT) for the peak hour was then used to evaluate the amount of time saved over the peak hour by the four ramp metering methods. The WATSim© output file provided MOEs related to travel time for each 15-minute time slot of the three-hour study period. Analysis of total travel times allows us to estimate the amount of savings realized by ramp metering methods over the no-meter case for the entire freeway section included in the study. Table 7.1 presents a summary of average total travel times for the AM peak hour.

Table 7.1 Summary of travel times for the AM peak hour (base year volume).

Metering Cases	ATTT (hrs)	Difference (hrs)
No metering	1054.91	-
Local responsive	1053.07	-1.84
Denver	1053.11	-1.8
Minnesota	1053.75	-1.16
Seattle	1056.43	1.52

The difference in the total travel times for the freeway segment among the different metering methods seemed very small—about 0.2% reduction in the AM peak hour. One-way ANOVA test showed that the average total travel times were not significantly different among them at a 95% confidence level (p = 0.659). Two possible reasons for this result are: 1) traffic volumes are too low for the metering methods to show their benefits or 2) ramp metering methods are not effective. Since many ramp metering methods have been reported to be effective, we discarded the second possibility and decided to increase the demand to the levels that may take place in the future at this segment of I-15 (see section 7.3).

7.2.2.2 PM peak hour

Figures 7.4a through 7.4d illustrate the density profiles along the freeway section in the study area at 15-minute intervals during the PM peak hour from 4:45 PM to 5:45 PM.

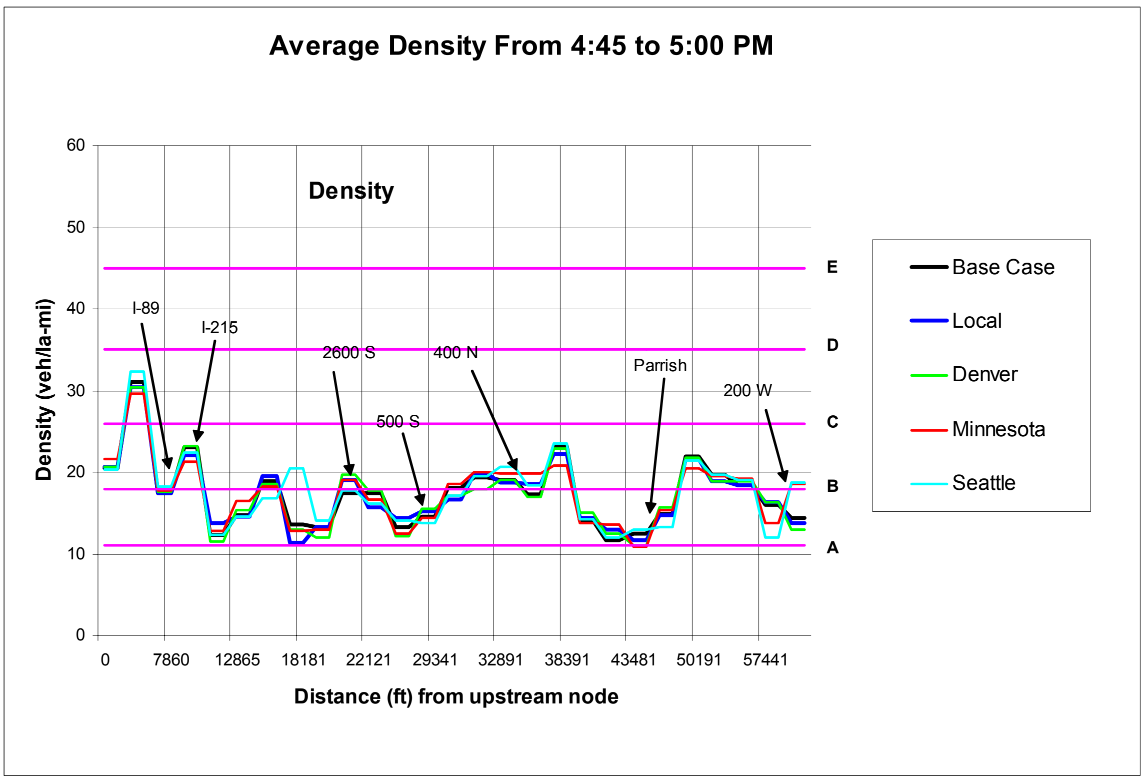

Figure 7.4a Average density profile for 4:45 PM to 5:00 PM (base year volume).

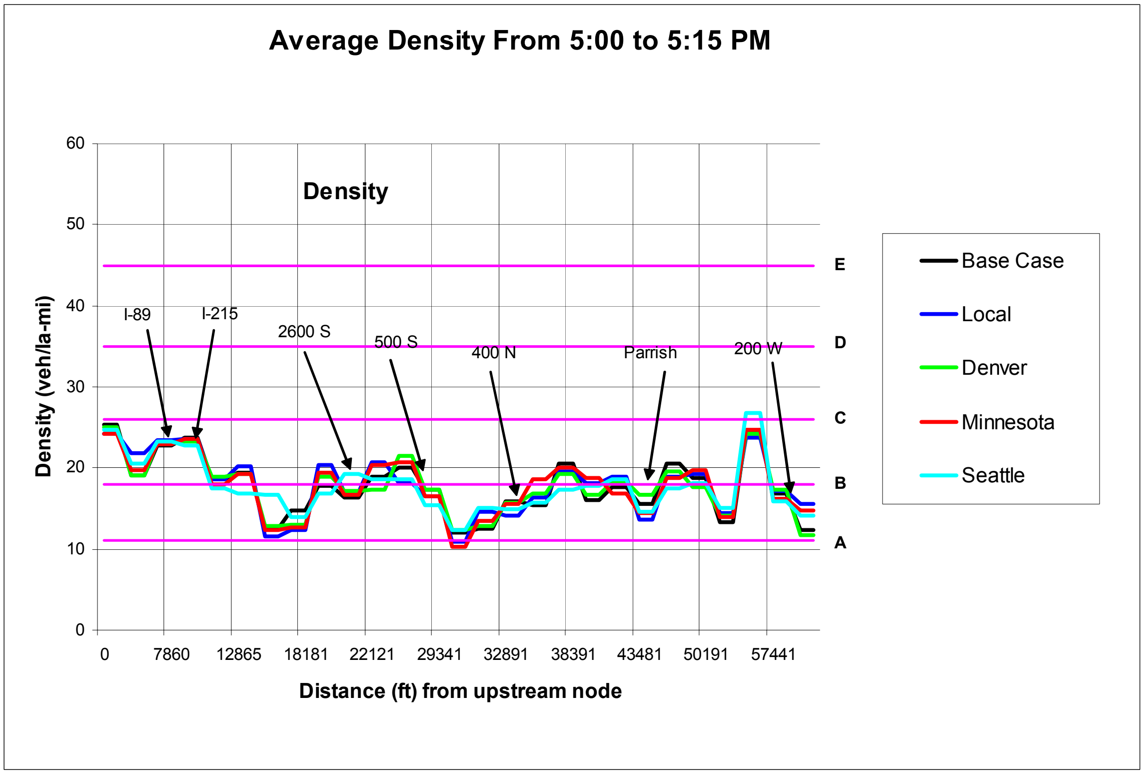

Figure 7.4b Average density profile for 5:00 PM to 5:15 PM (base year volume).

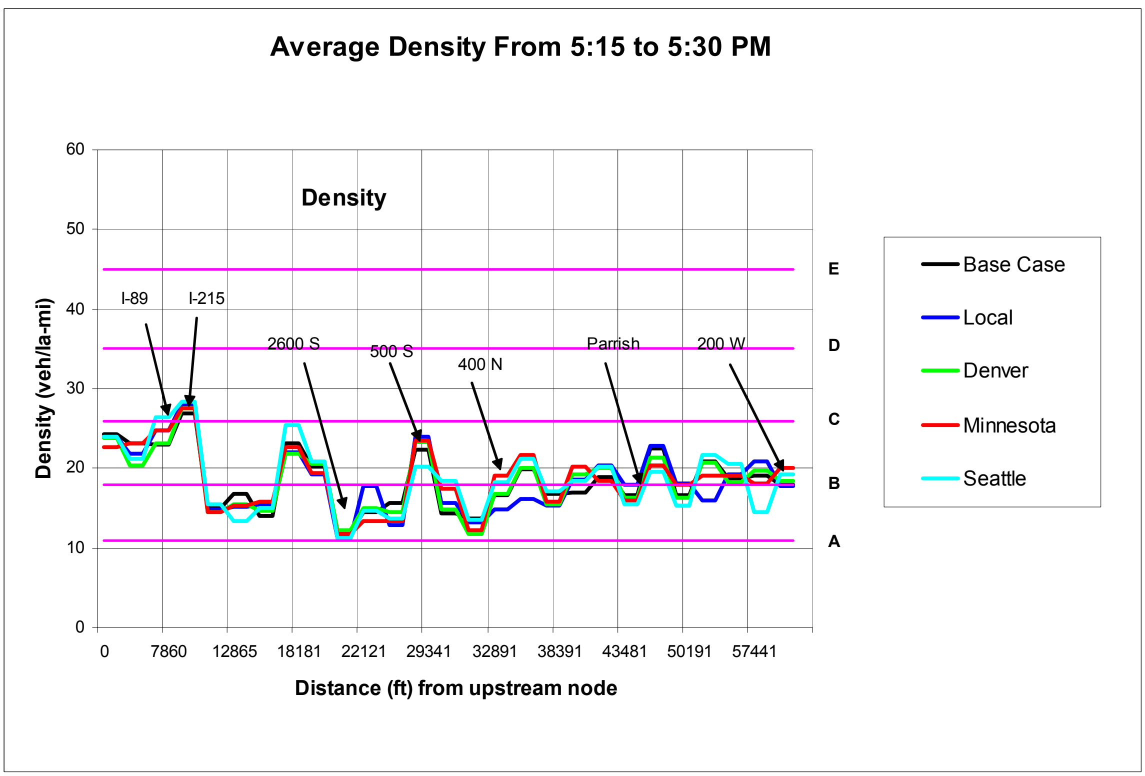

Figure 7.4c Average density profile for 5:15 PM to 5:30 PM (base year volume).

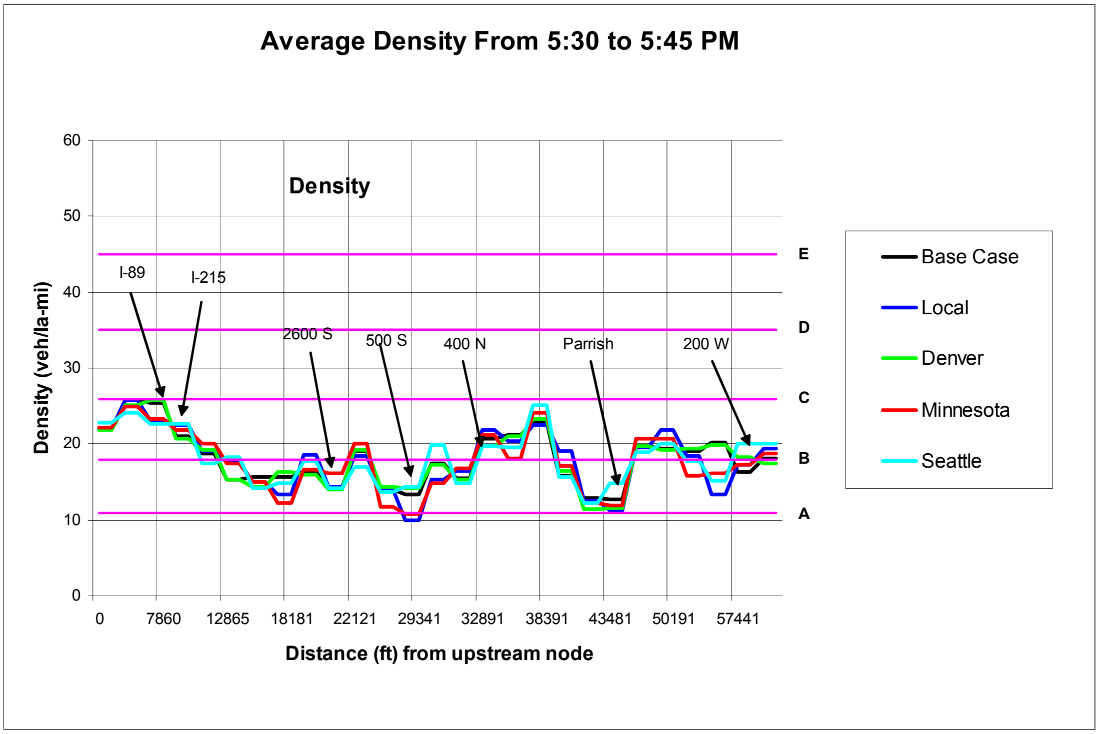

Figure 7.4d Average density profile for 5:30 PM to 5:45 PM (base year volume).

Similar to the AM peak, at the base year volume level the local and coordinated ramp metering methods did not make a significant impact on density profile. The base year volume seemed to be too small for these control methods to achieve their potential in stabilizing traffic flow on the freeway. The density profiles looked similar to each other, again requiring an increase in traffic volume to further evaluate the effect of the four ramp metering methods.

As was done for the AM peak, Table 7.2 shows the difference in average total travel time (ATTT) along the freeway section of the study area. The difference in ATTT among the studied cases shown in Table 7.2 is slightly larger than differences observed during the AM peak hour. The Denver Helper algorithm had the largest savings in total travel time, approximately 17.5 vehicle hours over the no-metering case (about a 2% reduction in total travel time for the PM peak hour). One-way ANOVA test showed that there was a statistically significant difference between the ATTT for the metered cases and the no-meter case at a 95% confidence level ($p = 0.000$).

The difference in travel time among the cases is reflected in user costs. A rough estimate of user cost savings is demonstrated here. For example, the study site with the Denver Helper algorithm—14.4 hours saving in total travel time over the no-meter case—would save approximately $43,750 annually over the no-meter case, assuming that the average wage of the drivers using this section is about $10.00 per hour and there are 250 work days in a year. Since the studied section is only 10 miles, the savings could be much larger and more significant if the entire freeway system in the Wasatch Front region is equipped with ramp meters.

Table 7.2 Summary of travel times for the PM peak hour (base year volume).

Metering Cases	ATTT (hrs)	Difference (hrs)
No metering	914.05	[redacted]
Local responsive	902.99	-11.06
Denver	896.64	-17.41
Minnesota	900.42	-13.63
Seattle	898.28	-15.78

7.3 Twenty Percent Increase in Traffic Volume

To evaluate future conditions in ten years along the study corridor, traffic volumes of the study area were increased by 20% over the base year volume (this analysis was done as a sensitivity analysis). Volumes were increased at all entry nodes in the WATSim© model, including both side street and freeway entry points. The following subsections illustrate the effects of the 20% increase in traffic volume on density profiles and total travel times.

As the volume increases, the possibility of having bottlenecks on the surface streets increases because I-15 has much more capacity than the nearby intersections on surface streets. Since the features of surface streets are not modified for increased volumes due to too many unknown factors, it is possible that freeway off-ramps may be blocked by queues created by the bottlenecks on surface streets. Conversely, surface street bottlenecks can limit the amount of vehicles that can enter the freeway. Therefore, two situations were simulated: 1) without bottlenecks on surface streets and 2) with bottlenecks on surface streets. The first situation allowed us to evaluate the performance of ramp metering methods without interference from the bottlenecks on surface streets. The second situation allowed us to evaluate whether the ramp metering methods evaluated in the study can properly react to the congestion on off-ramps caused by bottlenecks on surface streets. Turning volume percentages at an intersection on the east side of the interchange at Parrish Lane was manipulated to create these two situations.

7.3.1 Without bottlenecks on surface streets

This section summarizes the results of simulation runs for the no-metering and the four ramp metering methods with no bottlenecks on surface streets. Demand volumes were increased by 20% throughout the simulated area. The freeway section was now much more crowded with vehicles, as shown in the following discussions. We began to see differences in the density profiles at this volume level. At a few locations, especially between the I-215/I-15 junction and 500 South, we began to see some differences in the performance of the evaluated ramp metering methods.

7.3.1.1 AM peak hour

Figures 7.5a through 7.5d illustrate the density profiles along the freeway in the study area at 15-minute intervals during the AM peak hour from 7:45 AM to 8:45 AM.

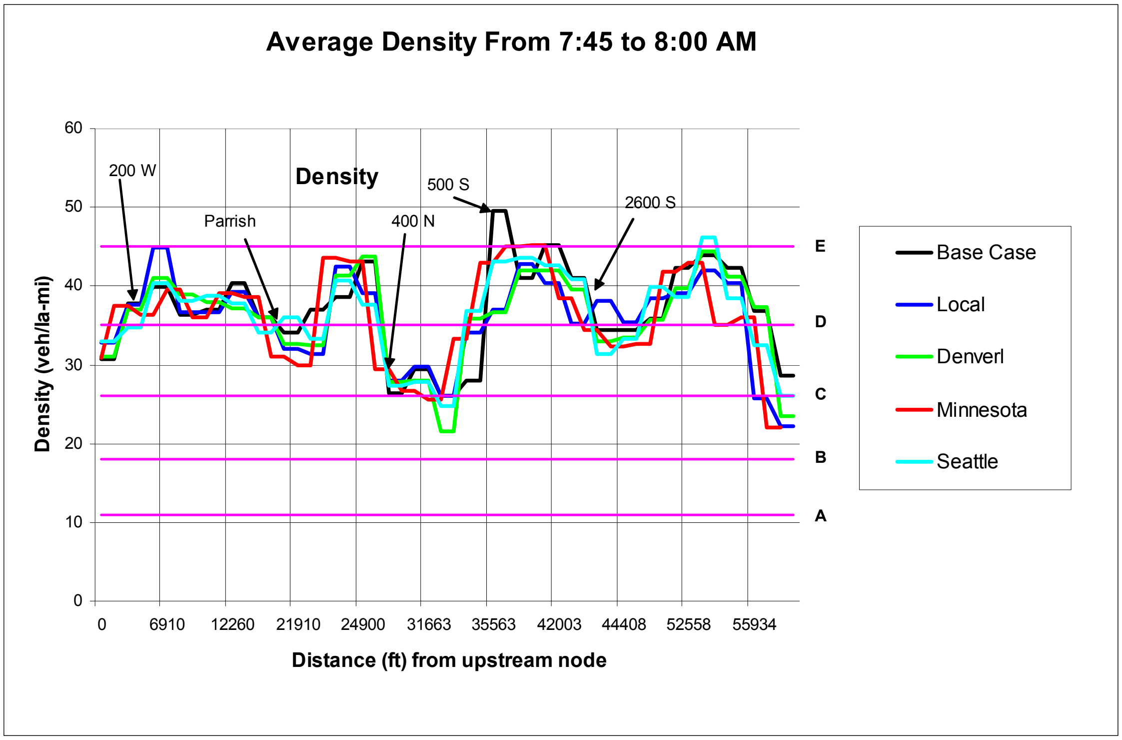

Figure 7.5a Average density profile for 7:45 AM to 8:00 AM (20% volume increase).

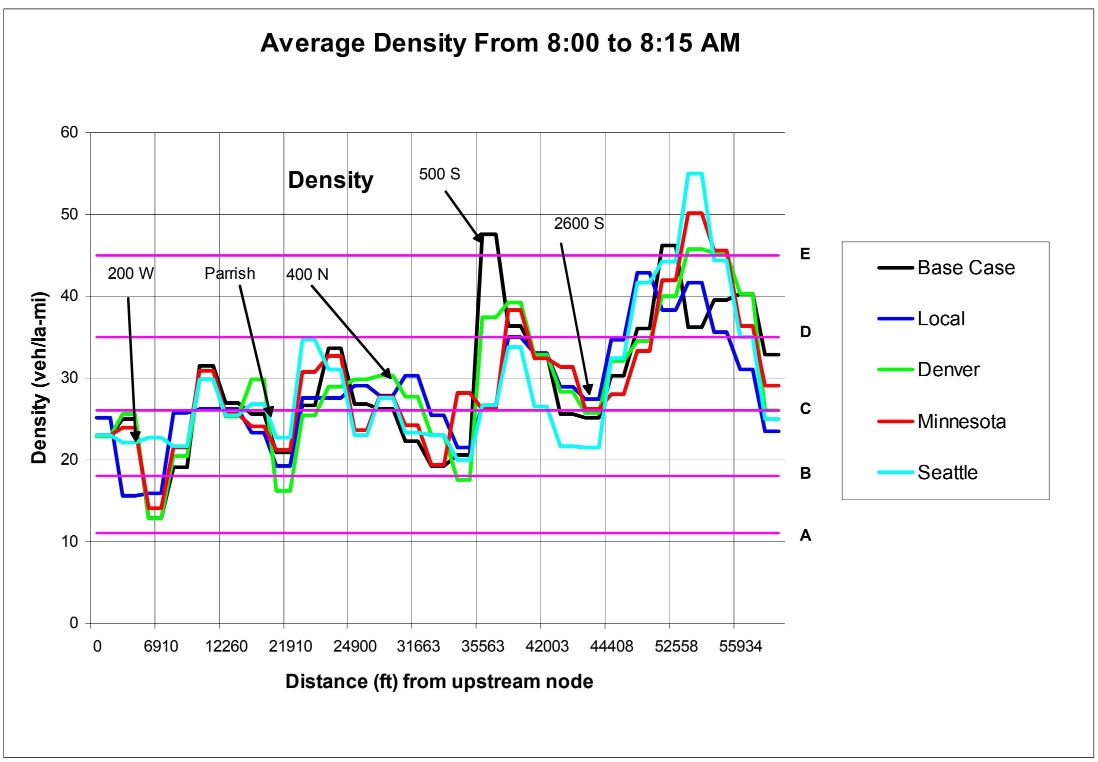

Figure 7.5b Average density profile for 8:00 AM to 8:15 AM (20% volume increase).

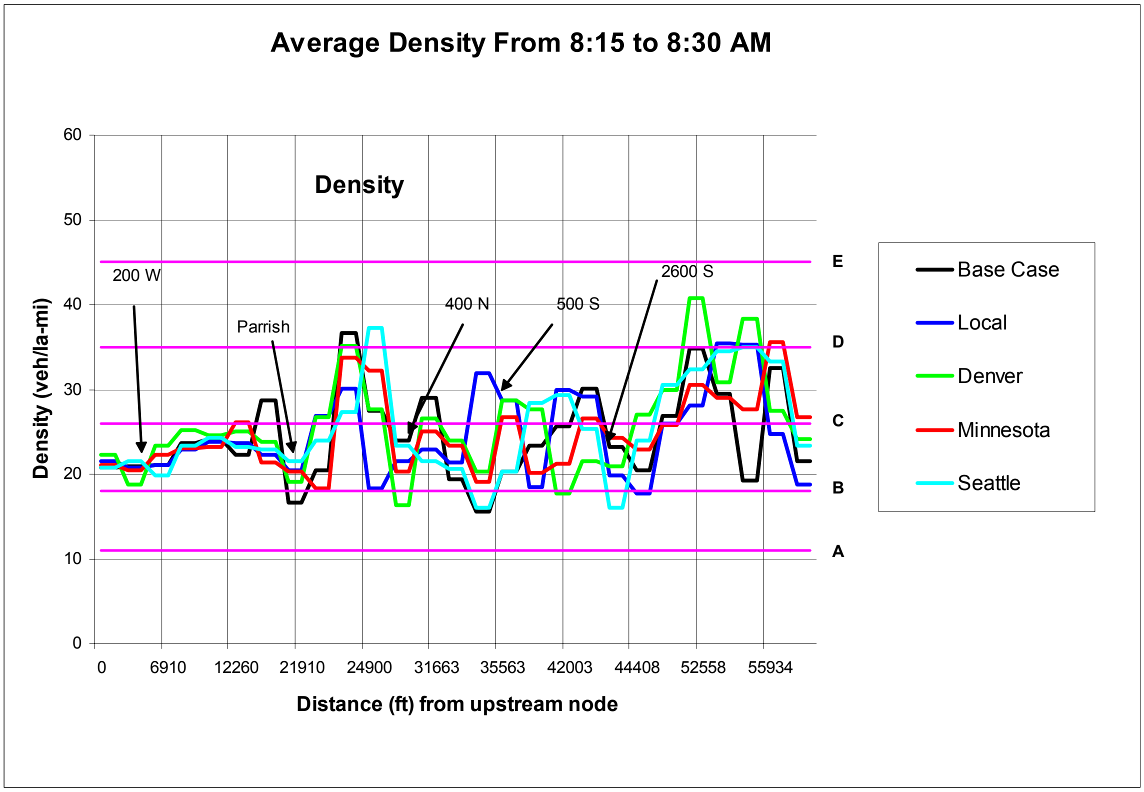

Figure 7.5c Average density profile for 8:15 AM to 8:30 AM (20% volume increase).

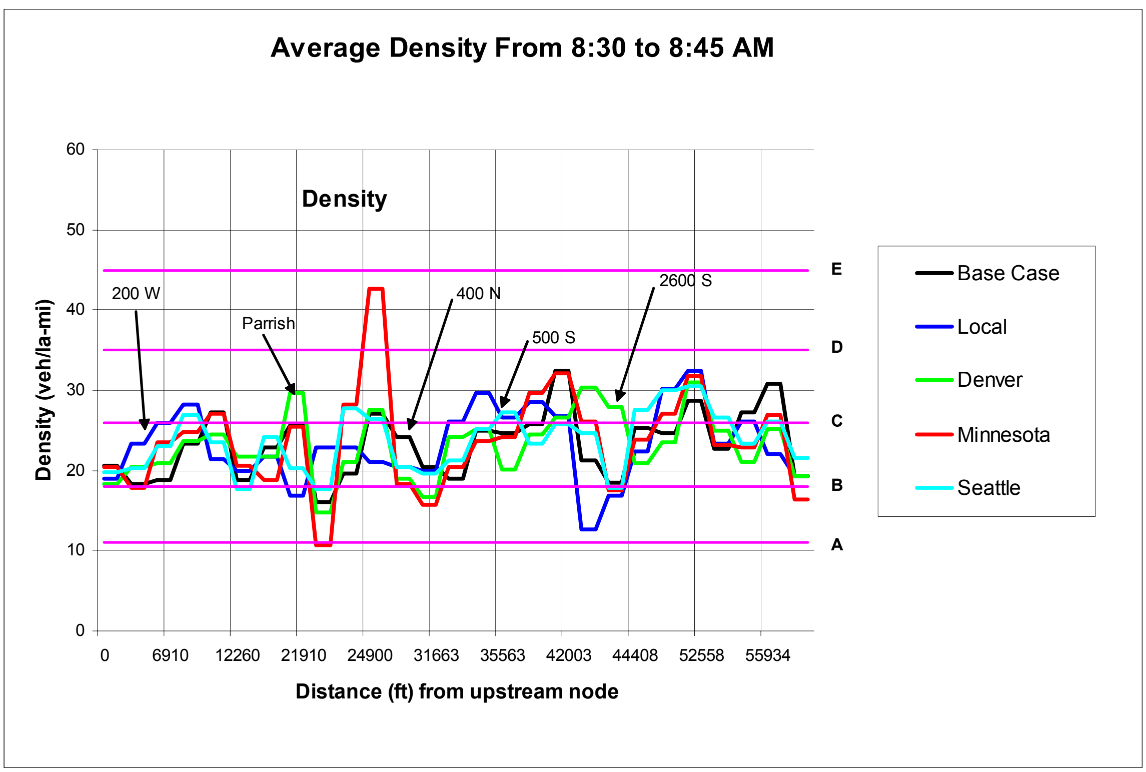

Figure 7.5d Average density profile for 8:30 AM to 8:45 AM (20% volume increase).

The twenty percent increase in the demand greatly affected the performance of the freeway and created density profiles that are dramatically different from the base year volume cases, as seen in Figures 7.5a through 7.5d. At two locations in the southbound direction, namely near 500 South and just north of the I-215/I-15 junction the level of service reached F for the no-metering case between 7:45 AM and 8:15 AM. At 500 South, all the ramp metering methods tested performed well to improve the level of service from F to E or D. North of the I-215/I-15 junction, none of the ramp metering methods have detectors necessary for their algorithms; hence it was expected that they would not perform well. However, the local metering method turned out to perform best at this location (see Figure 7.5b). Overall, the local responsive metering performed more consistently than the other three coordinated metering methods during the AM peak period with the 20% volume increase.

Since the entry volumes were increased by 20%, we expected average total travel time (AATT) to increase by at least 20%. Table 7.3 shows the ATTT along the freeway section. It appears none of the tested coordinated ramp metering methods was able to handle the added volume better than the no-metering case. The local responsive metering resulted in best performance.

Table 7.3 Summary of travel times for the AM peak hour (20% volume increase).

Metering Cases	ATTT (hrs)	Difference (hrs)
No metering	1329.82	[redacted]
Local responsive	1318.48	-11.34
Denver	1330.52	0.70
Minnesota	1329.80	-0.02
Seattle	1329.72	-0.10

7.3.1.2 PM peak hour

Figures 7.6a through 7.6d illustrate the density profiles of the 20% increase along the freeway in the study area at 15 minute intervals during the PM peak hour from 4:45 PM to 5:45 PM. Congestion is much more prominent at this time (compare Figure 7.6a through Figure 7.4d with Figure 7.4a through Figure 7.4d), when compared to the level of service under the base year volume. Note that the congestion south of Beck St. is created by the existing reverse curve alignment. The congestion at this location in the PM peak hour was also observed during the field study. There is no metering in this area; hence it is expected that this entry segment would be congested. Past the Beck St. on-ramp, the density profiles stabilize and the overall LOS of the section remains at C to D. Between 500 South and 400 North, LOS reaches F with no ramp metering. All the metering methods seem to work except at a couple of locations. The worst segment is between 500 South and 400 North between 5:15 PM and 5:30 PM. During this time, LOS on the freeway reaches F. All metering methods except the Minnesota Zone algorithm seem to work to maintain a moderate level of service. The Denver Helper algorithm was not able to cope with the congested traffic between 400 North and Parrish Lane, as shown in Figure 7.6c.

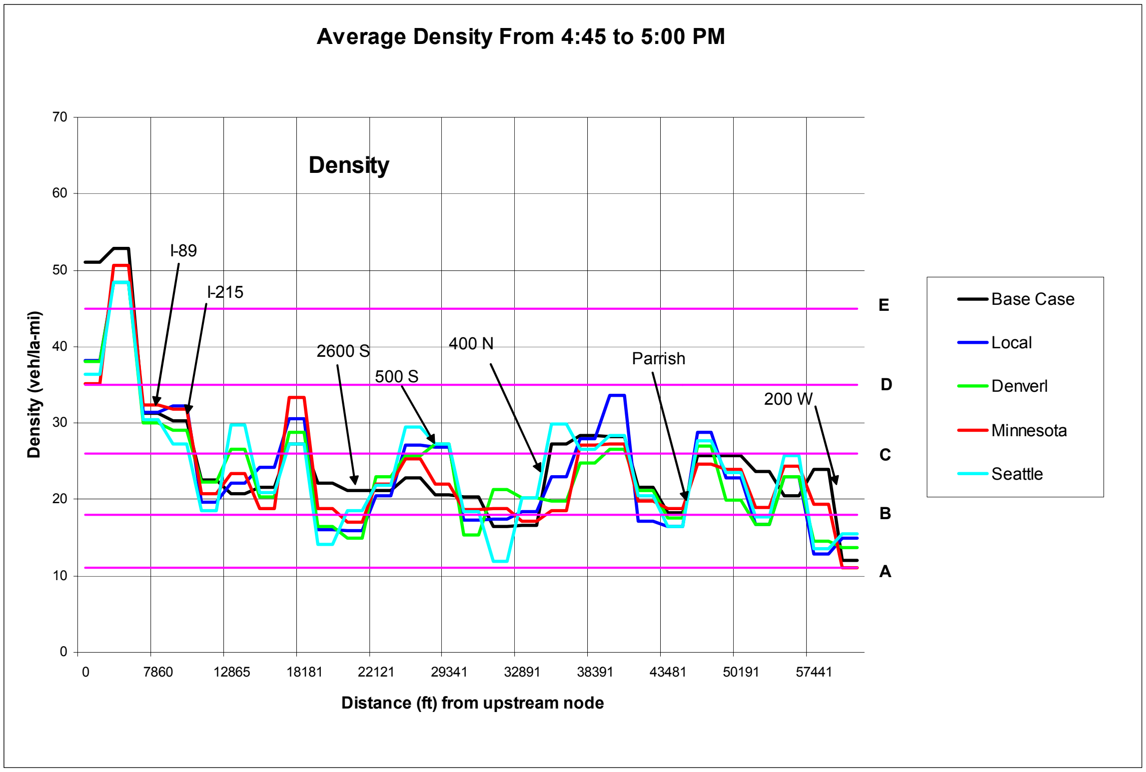

Figure 7.6a Average density profile for 4:45 PM to 5:00 PM (20% volume increase).

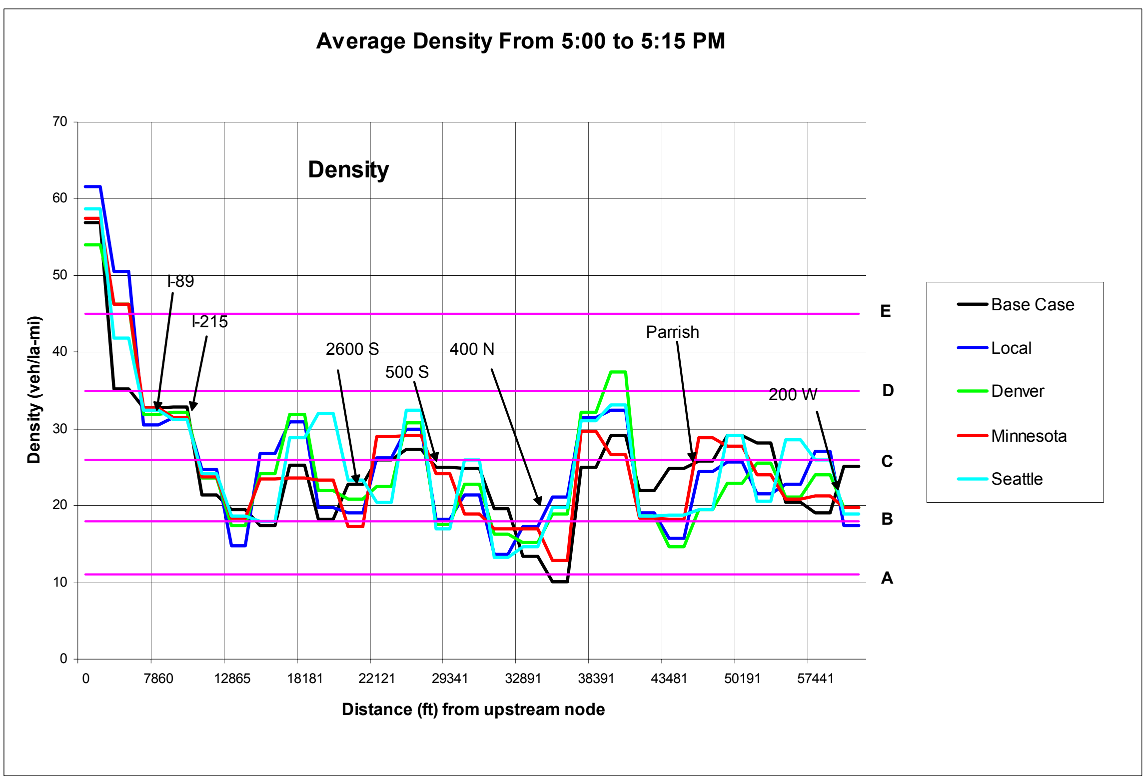

Figure 7.6b Average density profile for 5:00 PM to 5:15 PM (20% volume increase).

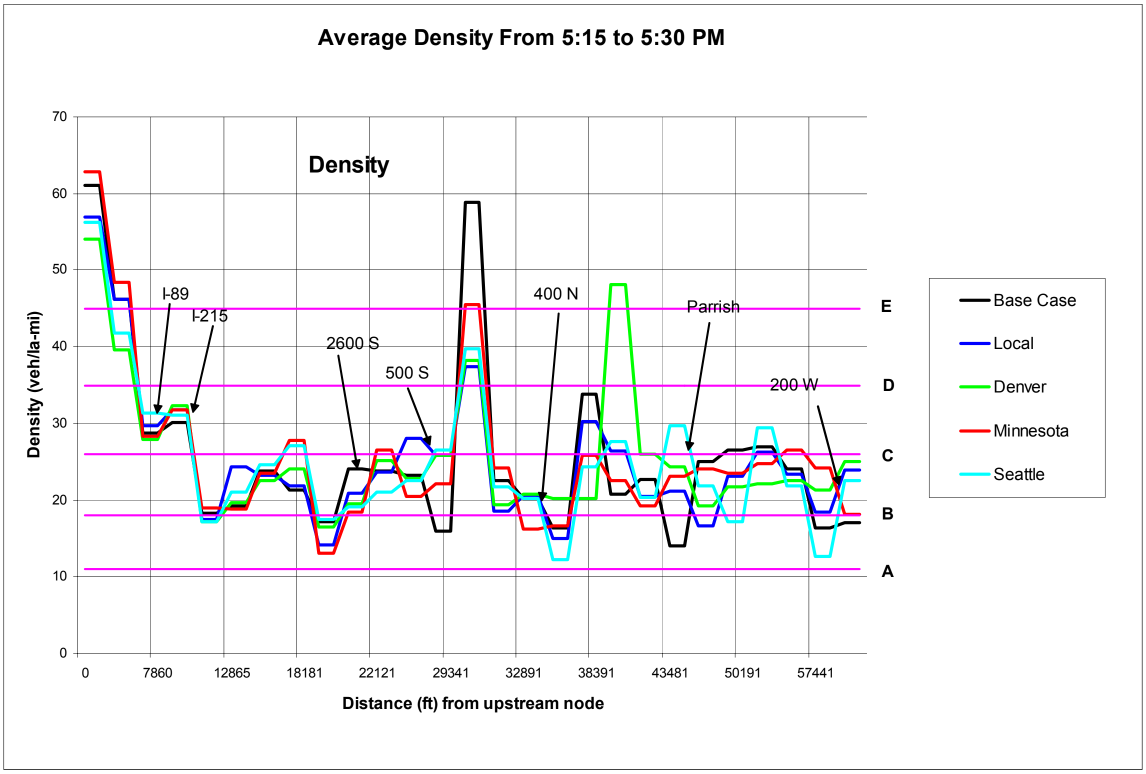

Figure 7.6c Average density profile for 5:15 PM to 5:30 PM (20% volume increase).

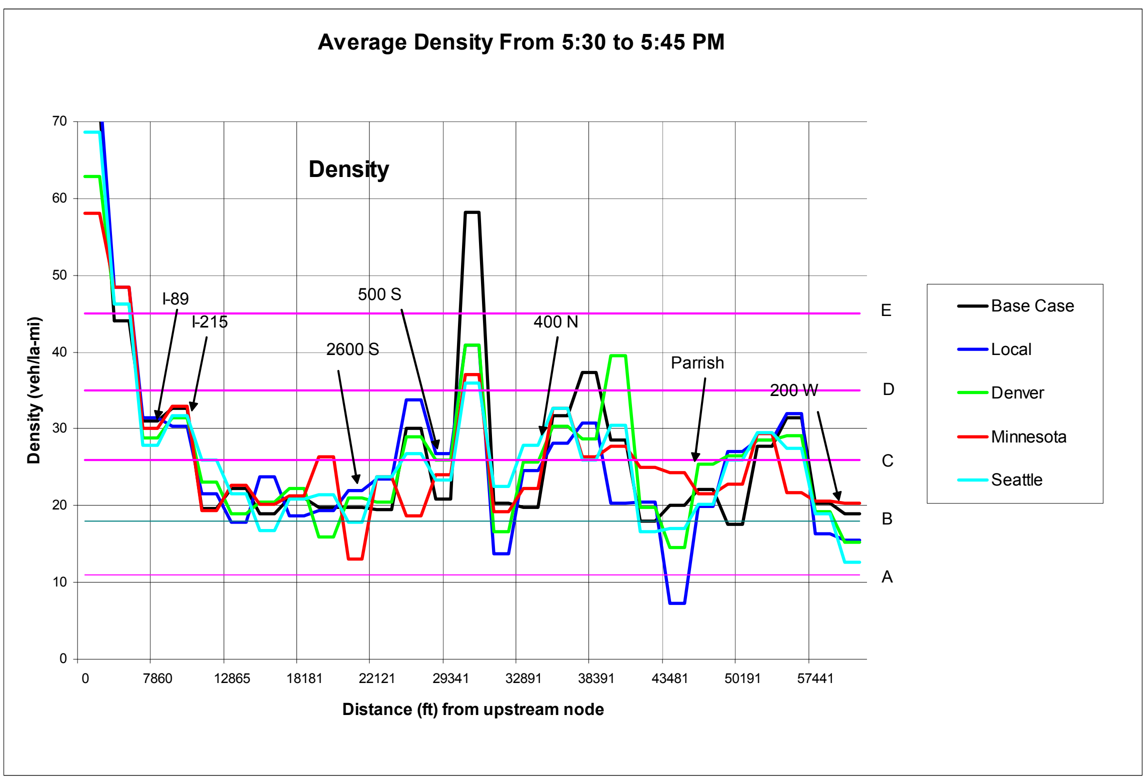

Figure 7.6d Average density profile for 5:30 PM to 5:45 PM (20% volume increase).

Table 7.4 illustrates the average total travel time (ATTT) along the freeway section with the 20% increase in volume. The difference between the metering cases and the no-metering cases is larger than that observed from the AM peak hour. Among the methods tested, the local responsive metering was still a better performer than the coordinated ramp metering methods. Approximately 20.5 vehicle hours were saved during the PM peak hour, that is, about a 2% reduction (see Table 7.4). This savings in time would translate into an annual savings of approximately $51,100 (20.44 hours x $10/hour x 250 work days/year = $51,100) for the 10-mile segment of the freeway.

Table 7.4 Summary of travel times for the PM peak hour (20% volume increase).

Metering Cases	ATTT (hrs)	Difference (hrs)
No metering	1084.02	[redacted]
Local responsive	1063.58	-20.44
Denver	1073.42	-10.60
Minnesota	1076.17	-7.85
Seattle	1066.77	-17.25

7.3.2 With bottlenecks on surface streets

The simulation runs performed in sections 7.3.1 were rerun with a change in turning volume on a small surface street near Parrish Lane that would help create an artificial bottleneck at intersections just east of the signalized intersection serving on- and off-ramps to I-15. During the simulation runs it was found that congestion due to the traffic on off-ramps would take place only in the PM peak period. There was not much traffic coming off the freeway in the southbound direction in the AM peak period. Therefore, only the PM peak period was simulated with artificial bottlenecks. Simulation runs were made for the no-metering case and for all four ramp metering methods evaluated in the study

Figure 7.7 illustrates the location where an artificial bottleneck was created. In reality vehicles exiting Parrish Lane onto the frontage road in this area would not turn back to Parrish Lane except to patronize a McDonald's restaurant and a gas station. Turning movement ratios were changed so that the link connecting the frontage road and Parrish Lane at a stop sign-controlled intersection would be clogged (see the explanations in Figure 7.7). To recreate the bottleneck, twenty percent of the traffic was forced to turn left on this link.

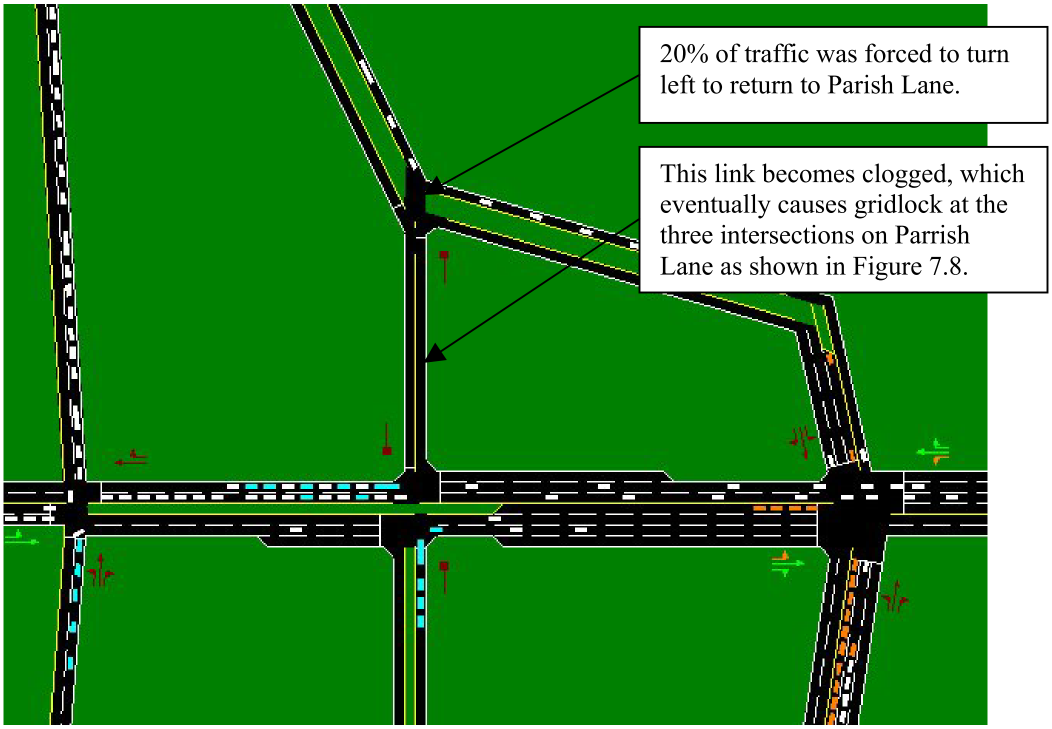

Figure 7.7 Screen shot of the location where turning volume was modified, east side of Parrish Lane.

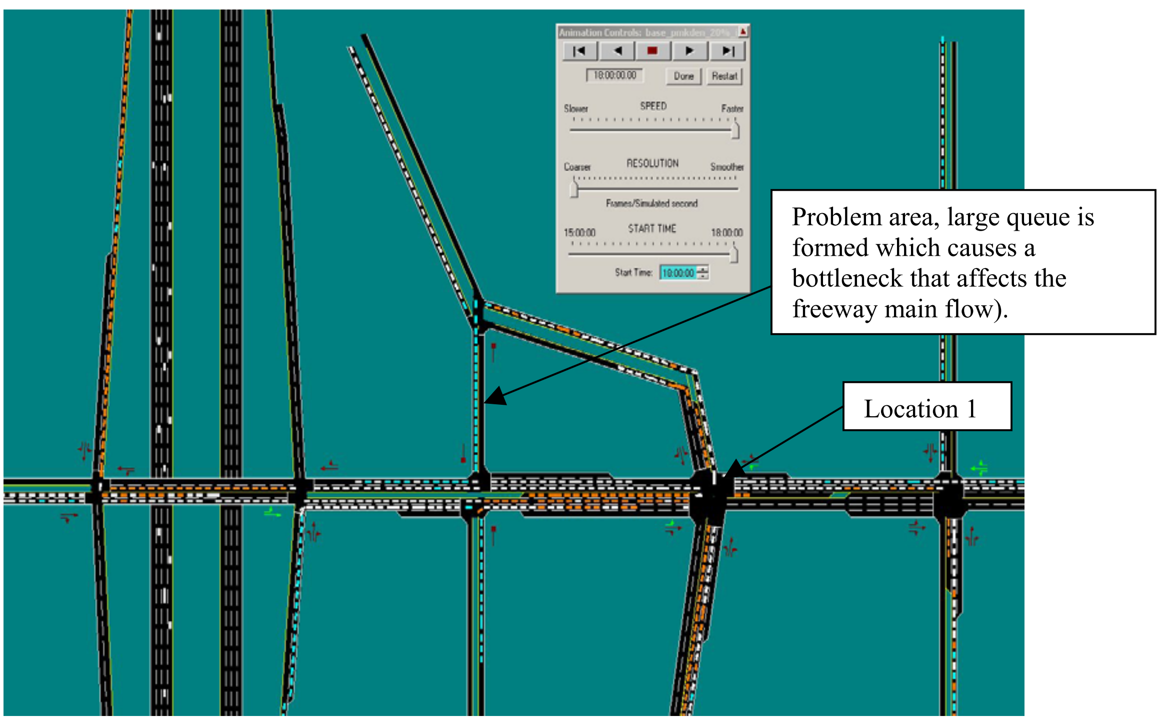

Figure 7.8 Screen shot of the location where grid lock begins, affecting Parrish Lane NB off-ramp.

As shown in Figure 7.8, the surface street heading south onto Parrish lane from the frontage road causes a backup that hinders the movement of the east bound left turn traffic, creating a gridlock on the frontage road leading to Parrish Lane at Location 1 in the figure. This gridlock in turn blocks left-turn vehicles trying to enter the frontage road. The gridlock quickly extends to the signalized intersection at the end of the northbound Parrish Lane off-ramp. Vehicles on the off-ramp quickly form a long queue which extends into the main flow of the freeway, clogging up the entire flow just south of the off-ramp, as shown in Figure 7.9.

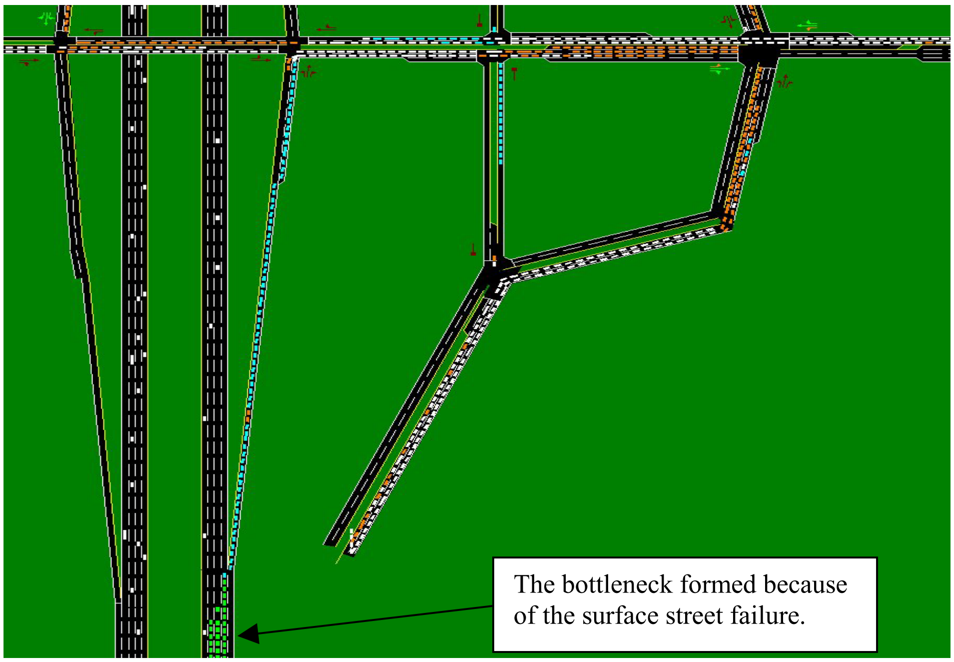

Figure 7.9 Screen shot of the location where backed-up queue begins to affect freeway main flow near Parrish Lane NB off-ramp.

This main-flow blockage problem that occurred without ramp metering also took place with the local responsive, Denver Helper, and Minnesota Zone algorithms. At this point, the MOE values in the simulation became unreliable; therefore no density diagrams were produced to illustrate changes in the density profiles. Similarly, average total travel times were not computed for the same reason.

The Seattle Bottleneck algorithm, however, did not experience the above problem. It behaved quite differently. The Seattle algorithm seemed to have more restrictive entry control at the ramps upstream of Parrish Lane, which reduced the amount of traffic coming off the freeway. However, the restrictive metering upstream created a queue backup problem at one of the upstream on-ramps, as shown in Figure 7.10. The queue backup from the northbound on-ramp at 500 South extended to the link on 500 South and eventually clogged up the intersection of 500 South and State Route 89. As was the case with the other metering methods, the MOE values became unreliable. Therefore, no density diagrams were produced for this case, and average total travel times were not computed.

Figure 7.10 Screen shot of the location where queue backup from off-ramp clogs up surface streets, near 500 South NB on-ramp.

7.4 Forty Percent Increase in Traffic Volume

To evaluate future traffic conditions in twenty years, the freeway traffic volumes of the study area were increased by forty percent over the base year volume (see Chapter 6 to find how this increase was estimated). Volumes were increased at all entry nodes in the WATsim© model, including both side streets and freeway entry points. The following subsections illustrate the effects of the forty percent increase.

As the volume increased by forty percent, the possibility of having bottlenecks on the surface streets also increased, as was the case with the twenty percent increase (see section 7.3). Since the AM cases had no freeway bottlenecks observed with the twenty percent volume increase, initial locations of potential bottlenecks, if any, were investigated. As for the PM cases, it was expected that the added volume would most likely affect the same locations.

7.4.1 AM peak hour

Figures 7.11a and 7.11b illustrate the locations where bottlenecks happened. For comparison purposes, simulation runs were conducted for all cases.

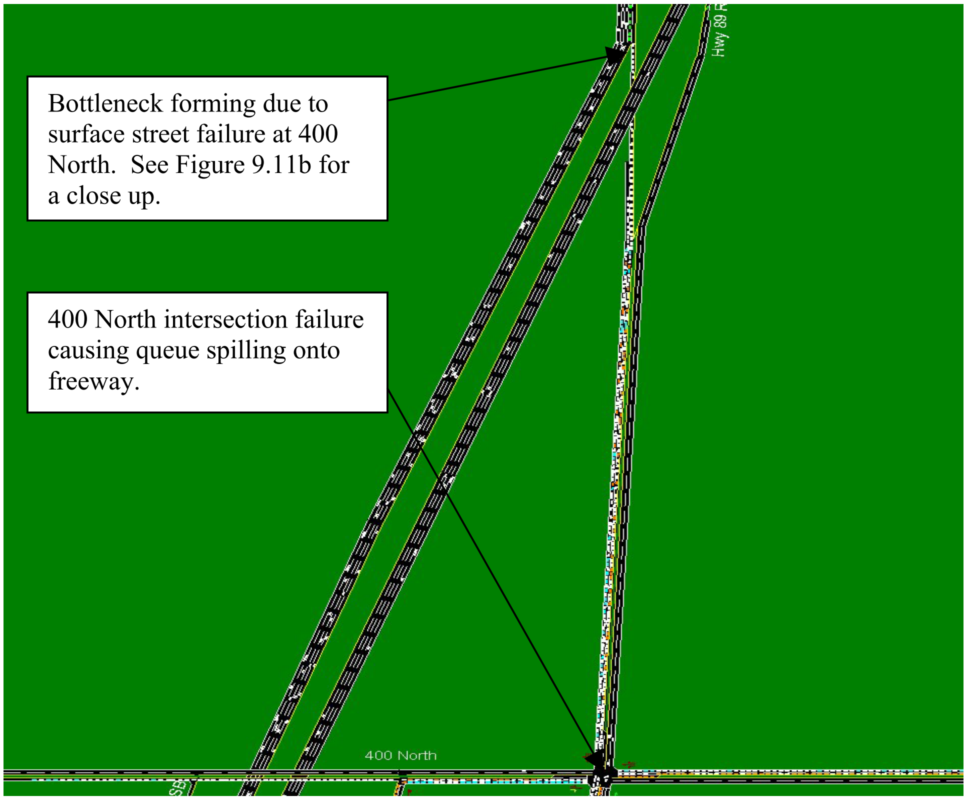

Figure 7.11a Screen shot of the location where queue initially forms on surface streets at 400 North.

As shown in Figure 7.11a, the surface street heading south onto 400 North from the freeway off-ramp is clogged, affecting the vehicles wanting to exit I-15. Vehicles on the 400 North southbound off-ramp quickly form a long queue into the main flow of the freeway, clogging up the entire flow just north of the off ramp, as shown in Figure 7.11b.

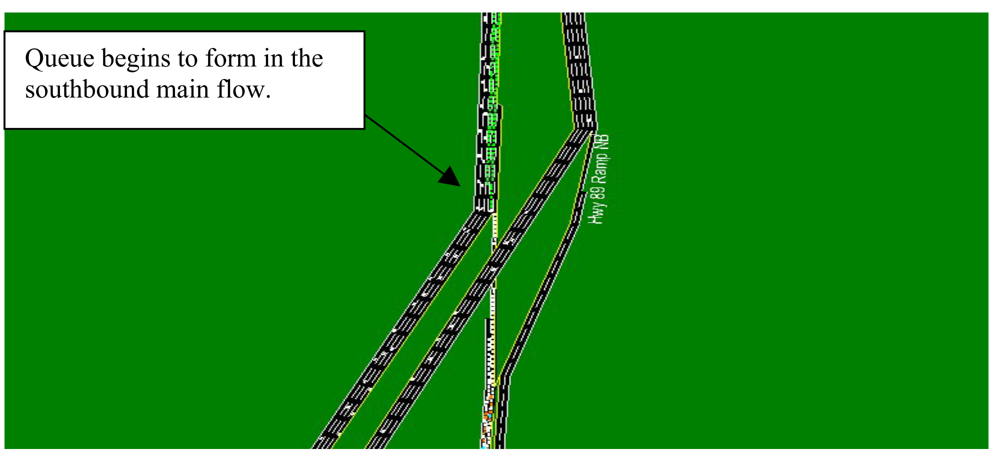

Figure 7.11b Screen shot of the location where backed-up queue begins affecting the freeway main flow.

This main-flow blockage problem that occurred under the no-metering condition also took place when the local responsive, Denver Helper, Minnesota Zone, and Seattle Bottleneck algorithms were simulated. At this point the MOE values in the simulation became unreliable; therefore no density diagrams were produced to illustrate changes in the density profiles. Similarly, average total travel times were not computed for the same reason.

7.4.2 PM peak hour

Figures 7.12 and 7.13 illustrate the locations where initial bottlenecks took place. For comparison purposes, simulation runs were conducted for all cases.

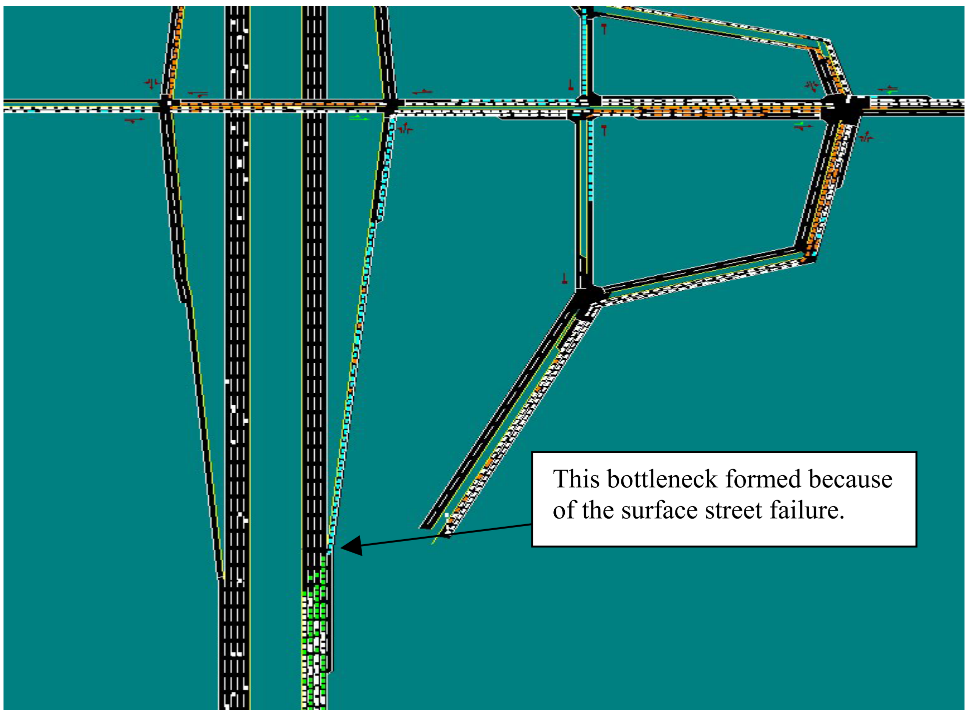

Figure 7.12 Screen shot of the location where queue back-up on off-ramp caused by surface street failure.

With a 40% increase in traffic volumes, the locations that had problems with the 20% increase again had bottleneck problems. The main-flow blockage problem that occurred under the no-ramp metering case also took place with the local responsive, Denver Helper, and Minnesota Zone methods.

As for the Seattle Bottleneck algorithm, the location (500 South NB on-ramp) that became a bottleneck with a 20% volume increase again had a bottleneck problem, as shown in Figure 7.13. With a 40% increase in volume the effect of this bottleneck was far more extensive. The intersection at 400 North and Route 89 was clogged and the gridlock effect spread to other intersections in the north end of the study site and eventually blocked the freeway main flow. Again the Parrish Lane exit did not have a serious problem.

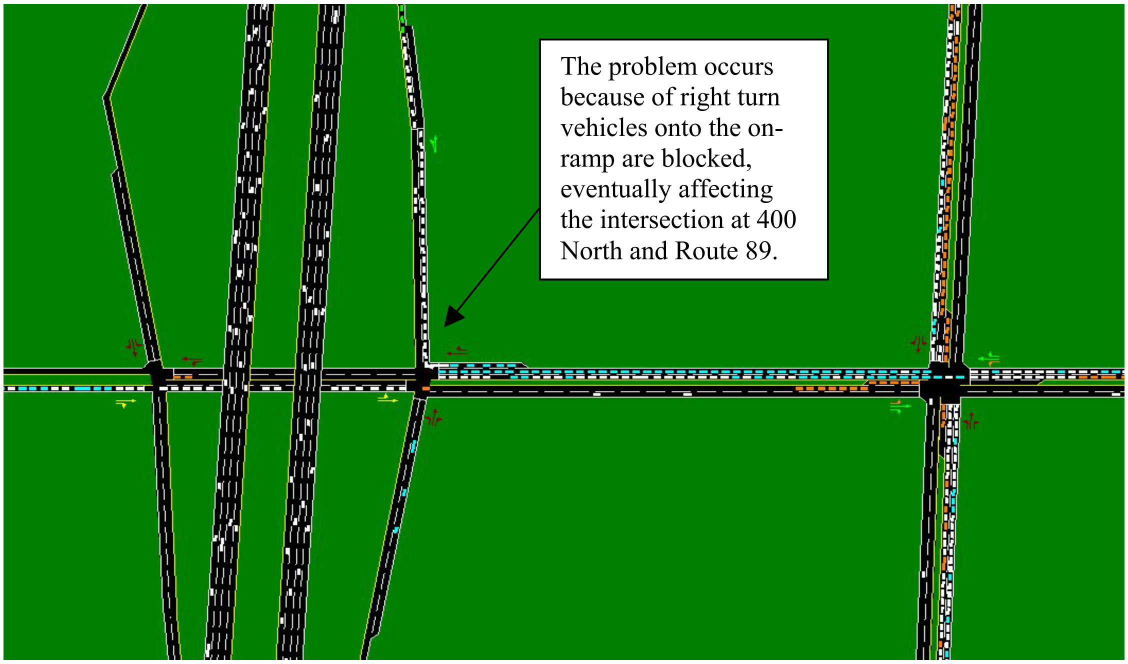

Figure 7.13 Screen shot of the location where queue backup from on-ramp clogs up surface streets.

The MOE values in the simulations with forty percent volume increase became unreliable at this point; hence no density profiles were produced. Similarly, average total travel times were not computed for the same reason.

7.5 Comparison of Travel Time of Freeway Main Flow

In this section results of the travel time analysis for the freeway main flow are presented. First the results of the peak one-hour analysis are presented. In this analysis travel time for comparison is the average total travel time (ATTT) of three simulation runs for the entire 10-mile study section of I-15 and for one peak hour. There is a chance of masking the travel time saved by ramp metering when travel time is aggregated for such a long time and length; hence two other analyses were added. It was observed during the field study that the real peaking at the study section of I-15 was concentrated in about 30 minutes of the peak hour and severe congestion took place only at a few locations at the study section. Travel time savings due to metering was therefore analyzed for the peak 15-minute period for the entire study section of the freeway. Then, the heavily congested links were analyzed for each 15-minute interval of the AM and PM peak hours.

7.5.1 Peak one hour analysis

As outlined in Table 6.1, four hypotheses were set up to assess the effectiveness of ramp meter control methods. This section provides the results of the assessment done for the peak one hour for both in the AM and PM peak periods. Average total travel time (ATTT) of vehicles on the freeway was used to eliminate the influence of congestion on surface streets in the assessment. As can be seen in the tables in this section, overall improvement by ramp metering was small for the studied section of I-15; hence, formal statistical analyses to compare the mean total travel times were not conducted to test the significance of the difference in means.

7.5.1.1 Hypotheses 1 and 2

Hypothesis 1 and 2 test the superiority of the local-responsive and coordinated meter control methods against the no-metering case. Since these two can be combined, their evaluations were completed together. Table 7.5 and 7.6 illustrates the comparison between the ramp meter controlled cases against the no-metering case for both the base year volume (year 1998) and 20% increase (10 years in the future).

Table 7.5 Comparison between the local and coordinated ramp metering methods vs. the no-metering case for the AM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
No Metering	1054.91	1329.82				
Local	1053.07	1318.48	-1.84	-11.34	-0.17%	-0.85%
Denver	1053.11	1330.52	-1.8	0.7	-0.17%	0.05%
Minnesota	1053.75	1329.8	-1.16	-0.02	-0.11%	0.00%
Seattle	1056.43	1329.72	1.52	-0.1	0.14%	-0.01%

Table 7.6 Comparison between the local and coordinated ramp metering methods vs. the no-metering case for the PM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
No Metering	914.05	1084.02				
Local	902.99	1063.58	-11.06	-20.44	-1.21%	-1.92%
Denver	896.64	1073.42	-17.41	-10.6	-1.90%	-1.00%
Minnesota	900.42	1076.17	-13.63	-7.85	-1.49%	-0.74%
Seattle	898.28	1066.77	-15.78	-17.25	-1.73%	-1.62%

As seen in Table 7.5, the local responsive method does reduce total travel time for vehicles on the freeway by nearly 0.2% for the base year volume and by about 1% for the twenty percent increase in volume in the AM peak hour. The difference may look small but this amounts to about $30,000 annual savings in user costs for the studied section of I-15. As for the coordinated methods for the base year volume, benefits are relatively small, and they are even smaller for the twenty percent increase in volume. This may imply that the coordinated methods may not produce benefits large enough for their installation expenses as far as the AM peak hour is concerned.

The performance of ramp meter control methods looked better for the PM peak hour for the study site, probably because more commuters get off the freeway in this section of I-15, creating congestion near off-ramps. From Table 7.6 we observe that the coordinated ramp meter control methods perform slightly better than the local responsive for the base year volume, but for the future volume the local responsive would perform better—by about 2% over the no-metering case. This shows that the local responsive method would handle the increase in volume better than the coordinated ramp meter control methods tested.

7.5.1.2 Hypothesis 3

Hypothesis 3 compares the performance of local responsive metering against the three coordinated ramp meter controls tested. Tables 7.6 and 7.7 present the comparison of travel time savings by the local responsive against the savings achieved by the coordinated ramp meter controls.

Table 7.7 Comparison between the local responsive metering and the coordinated metering methods for the AM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
Local	1053.07	1318.48				
Denver	1053.11	1330.52	0.04	12.04	0.00%	0.91%
Minnesota	1053.75	1329.8	0.68	11.32	0.06%	0.86%
Seattle	1056.43	1329.72	3.36	11.24	0.32%	0.85%

Table 7.8 Comparison between the local responsive metering and the coordinated metering methods for the PM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
Local	902.99	1063.58				
Denver	896.64	1073.42	-6.35	9.84	-0.70%	0.93%
Minnesota	900.42	1076.17	-2.57	12.59	-0.28%	1.18%
Seattle	898.28	1066.77	-4.71	3.19	-0.52%	0.30%

From Table 7.7 we can say that the local responsive performs a little better than the coordinated methods for the base year volume, but with the twenty percent increase in volume, the local responsive method performs better by almost 1%. This would indicate that the local responsive method would alleviate congestion better than the coordinated methods when the traffic volume increases on the freeway in the AM peak hour.

In the PM peak hour, the local responsive metering was slightly inferior to the coordinated control methods with the base year volume, but it works better by about 1%

when the volume increases by 20%. This result is similar to the AM peak hour. The local responsive metering seems to work better for this study site as the volume increases.

7.5.1.3 Hypothesis 4

Hypothesis 4 tests one coordinated ramp meter control over the other two. Table 7.9 was created to make the Denver Helper algorithm as the base for comparison for the AM peak hour. The differences between the Denver Helper algorithm and the other two methods show that the Denver algorithm would perform slightly better than the Minnesota Zone algorithm for the base year volume but slightly worse for the 20% volume increase case. Although, the Seattle algorithm performs better in the future condition, its performance was not consistent. Table 7.10 for the PM peak hour shows the differences are minimal among the coordinated metering methods.

Table 7.9 Comparison between the coordinated methods and the Denver Helper method for the AM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
Denver	1053.07	1330.52				
Minnesota	1053.75	1329.8	0.68	-0.72	0.06%	-0.05%
Seattle	1056.43	1329.72	3.36	-0.8	0.32%	-0.06%

Table 7.10 Comparison between the coordinated methods and the Denver Helper method for the PM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
Denver	896.64	1073.42				
Minnesota	900.42	1076.17	3.78	2.75	0.42%	0.26%
Seattle	898.28	1066.77	1.64	-6.65	0.18%	-0.62%

Tables 7.11 and 7.12 show the comparison between the Minnesota Zone algorithm and the Seattle Bottleneck algorithm; the Minnesota Zone algorithm was used as the base for comparison. Table 7.11 shows that the Minnesota Zone algorithm performs about the same as the Seattle Bottleneck algorithm for the AM peak hour. For the PM peak hour the Seattle Bottleneck algorithm seemed to perform slightly better than the Minnesota Zone algorithm.

Table 7.11 Comparison between the Minnesota Zone algorithm and the Seattle Bottleneck algorithm for the AM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
Minnesota	1053.75	1329.8	[redacted]	[redacted]	[redacted]	[redacted]
Seattle	1056.43	1329.72	2.68	-0.08	0.25%	-0.01%

Table 7.12 Comparison between the Minnesota Zone algorithm and the Seattle Bottleneck algorithm for the PM peak hour.

	ATTT (hrs)		Difference (hrs)		% Change	
Metering Cases	Base volume	20% increase	Base volume	20% increase	Base volume	20% increase
Minnesota	900.42	1076.17	[redacted]	[redacted]	[redacted]	[redacted]
Seattle	898.28	1066.77	-2.14	-9.4	-0.24%	-0.87%

7.5.2 Peak 15-minutes analysis

Travel time savings were evaluated for the 15-minute peak period. This was done because the study section was about 10 miles long and the real peaking takes place only for a short period. It was feared that the average total travel time (ATTT) savings might average out if it were evaluated over the one-hour peak period, masking the savings in the 15-minute peak period. Data were extracted from the same simulation files used for the peak one-hour analysis to make the outcomes consistent with the one-hour peak period analysis. The 15-minute peak period analysis was done only for the case where traffic volume was increased by 20% because the base year volume cases did not show a large difference in total travel time depending on the ramp metering method. The following tables provide a summary of the 15-minute analysis for both AM and PM peak periods. As was done for the peak hour analysis, the average total travel times (ATTT) of the metered cases were compared with the no-metering case. Since finding the peak 15-minute in the peak hour was difficult, two 15-minute peak periods were analyzed. These 15-minute peak periods were identified using the peak-hour analysis data.

Results of the analysis for the AM peak are shown in Tables 7.13 and 7.14. As shown in the tables, the percent change from one time slice to another differs between the 15-minute peak periods except for the Denver algorithm where the results are practically the same for each time slice. Nevertheless, overall changes are very small. Also, the percent changes in ATTT within the two peak 15-minute time slices are only slightly different overall.

Table 7.13 Comparison of average total travel times for the 7:45-8:00 AM 15-minute peak period (with 20% traffic volume increase).

Metering Cases	ATTT (hrs)	Difference (hrs)	% change
No Metering	386.78		
Local	382.38	-4.39	-1.1%
Denver	383.58	-3.19	-0.8%
Minnesota	383.82	-2.96	-0.8%
Seattle	383.93	-2.85	-0.7%

Table 7.14 Comparison of average total travel times for the 8:00-8:15 AM 15-minute peak period (with 20% traffic volume increase).

Metering Cases	ATTT (hrs)	Difference (hrs)	% change
No Metering	374.75		
Local	373.91	-0.84	-0.2%
Denver	371.62	-3.12	-0.8%
Minnesota	376.86	2.11	0.6%
Seattle	374.01	-0.73	-0.2%

Results of the analysis for the PM peak hour are shown in Tables 7.15 and 7.16. The percent change from one time slice to another is larger on average than those for the AM cases. These tables show that there are variations in the percent change in savings in total travel time within the one-hour peak period. When analyzed over one hour these changes are averaged out and the larger change found in individual 15-minute peak periods is hidden.

Although, Tables 7.13 through 7.16 only illustrate the comparison between the local and coordinated ramp metering methods versus the no-metering case and are only for the peak 15-minute intervals, ATTTs for the 15-minute peak periods were higher than the peak hour ATTTs. In other words, the amount of time saved during the peak 15 minutes expressed in percent was greater than that averaged over the peak hour. Since the true peak observed in the field lasted about 30 minutes, these tables show representative travel time savings during the peak period for the study section.

Table 7.15 Comparison of average total travel times for the 5:15-5:30 PM 15 minute peak period (with 20% traffic volume increase).

Metering Cases	ATTT (hrs)	Difference (hrs)	% change
No Metering	241.10		
Local	235.17	-5.93	-2.5%
Denver	234.25	-6.84	-2.8%
Minnesota	234.62	-6.48	-2.7%
Seattle	232.95	-8.14	-3.4%

Table 7.16 Comparison of average total travel times for the 5:30-5:45 PM 15 minute peak period (with 20% traffic volume increase).

Metering Cases	ATTT (hrs)	Difference (hrs)	% change
No Metering	236.09	[redacted]	[redacted]
Local	232.05	-4.04	-1.7%
Denver	227.28	-8.81	-3.7%
Minnesota	231.51	-4.58	-1.9%
Seattle	231.40	-4.70	-2.0%

7.5.3 Analysis of congested links

The observation of the density profiles for a 20% increase in traffic volume for both the AM and PM no-metering cases showed that certain links experienced level of service F. Thus, when total travel times are computed for the entire 10-mile section, large savings in travel time achieved by ramp metering in congested links may be masked. In order to analyze how much travel time savings are taking place at truly congested links, congested links with level of service of F and their upstream and downstream links were identified using the simulation outputs used for the previous analyses (see Figure 7.14). These links were then analyzed separately for savings in total travel time. Tables 7.17 and 7.18 present percent reductions in average total travel times for the AM peak hour and the PM peak hour. Simulation outputs used for the peak hour analysis were used to compute these changes. Note that positive values in these tables mean reductions (or savings) in travel time. These percentages were computed with the total travel time for the no-metering case as the reference value. The analysis was done for each 15-minute interval in the peak one hour and the link listed in the middle is the most congested link used for this analysis.

For the AM peak hour the coordinated metering cases performed well overall compared to the local responsive metering case as shown in Table 7.17. For instance, the Denver Helper algorithm achieved a 32% reduction in total travel time for the most congested link for the time period 8:15 to 8:30 AM. The Seattle Bottleneck algorithm performed well in the same time slice with a 16% reduction. The Minnesota Zone algorithm did not perform well in the same period, but achieved a 7% reduction in the next 15-minute time slice.

For the PM peak hour, however, percent reductions in total travel time were fairly small, similar to what has been presented in previous sections for the 20% increase in volume. Traffic volume during the PM peak is lower than the AM peak in this study segment. Among the metering methods, the Denver Helper algorithm seemed to be consistent in reducing total travel time at the congested links—the highest percent reduction in total travel time of 2.5% was achieved by the Denver Helper algorithm.

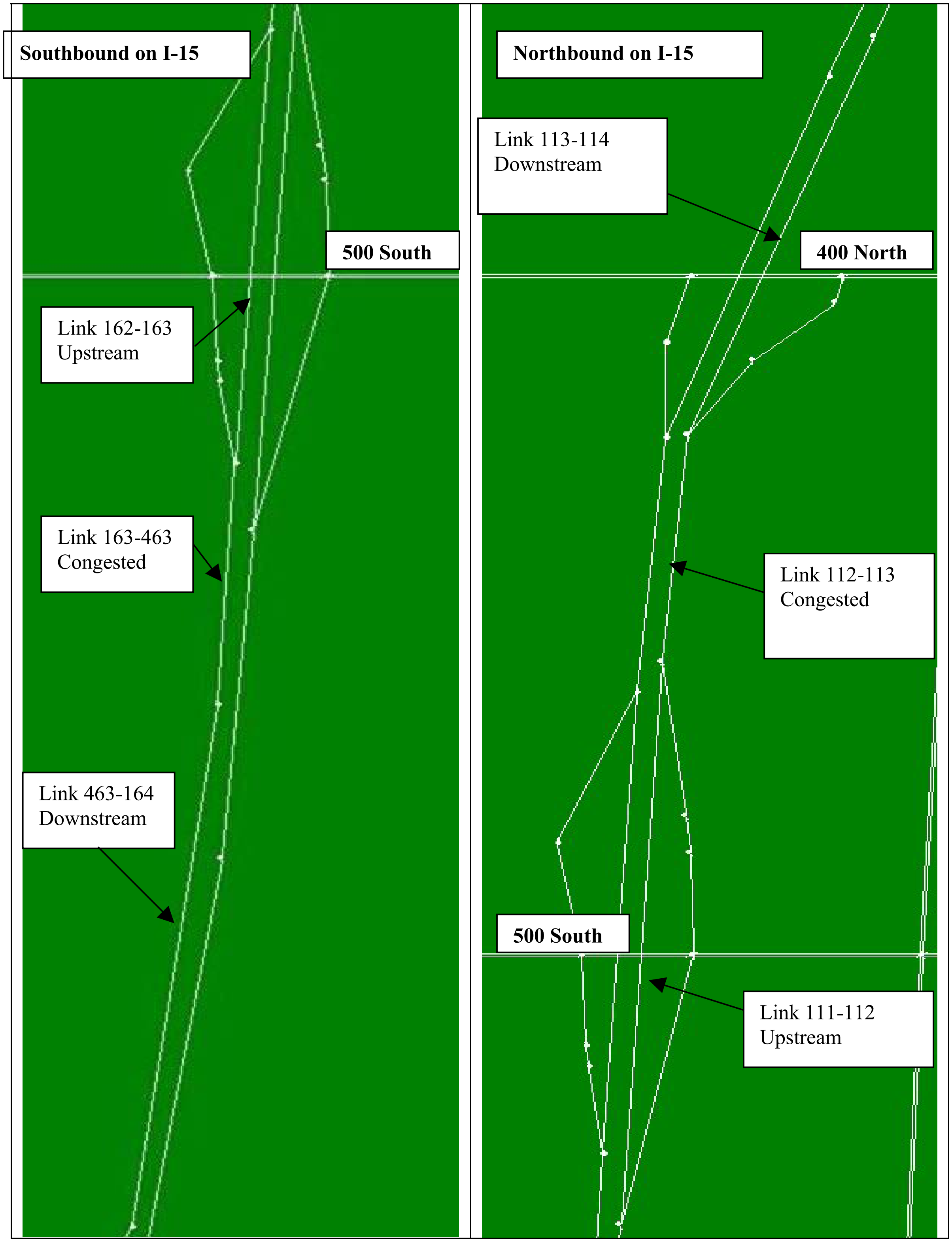

FIGURE 7.14 Screen shots of the congested links analyzed for the total travel time comparison.

Table 7.17 Percent reductions in total travel time in congested links for the AM peak hour (with 20% traffic volume increase).

Time Slice	Link		Denver	Minnesota	Seattle
7:45 AM-8:00 AM	162,163	0.96%	0.43%	1.33%	0.18%
	163,463	4.83%	4.90%	2.56%	-3.33%
	463,164	1.07%	0.58%	0.59%	-1.19%
8:00 AM-8:15 AM	162,163	10.50%	12.25%	9.46%	12.70%
	163,463	-8.17%	32.10%	1.17%	16.34%
	463,164	-2.09%	1.68%	-2.21%	-1.48%
8:15 AM-8:30 AM	162,163	-5.14%	-1.81%	-2.15%	-0.91%
	163,463	6.26%	6.16%	7.14%	8.53%
	463,164	1.80%	0.51%	1.22%	1.65%
8:30 AM - 8:45 AM	162,163	0.94%	-0.24%	-0.21%	0.33%
	163,463	-2.31%	-0.65%	-1.06%	0.14%
	463,164	0.02%	-0.28%	-0.62%	0.39%

Table 7.18 Percent reductions in total travel time in congested links for the PM peak hour (with 20% traffic volume increase).

Time Slice	Link	Local	Denver	Minnesota	Seattle
4:45 PM - 5:00 PM	111,112	-0.43%	-0.29%	0.01%	0.34%
	112,113	-0.36%	0.21%	0.57%	1.31%
	113,114	0.19%	0.37%	0.50%	0.49%
5:00 PM - 5:15 PM	111,112	0.78%	0.75%	0.73%	1.04%
	112,113	0.41%	0.36%	1.11%	0.97%
	113,114	0.33%	0.56%	0.36%	0.81%
5:15 PM - 5:30 PM	111,112	0.79%	1.86%	1.47%	0.70%
	112,113	1.65%	2.33%	2.33%	1.32%
	113,114	1.37%	1.27%	1.69%	1.07%
5:30 PM - 5:45 PM	111,112	1.14%	2.02%	1.37%	1.23%
	112,113	0.61%	2.29%	0.88%	0.32%
	113,114	0.63%	1.71%	1.72%	1.26%

It is interesting to note the PM peak hour had more reductions in total travel time than the AM peak hour, but when the most congested links under no-metering were analyzed the AM peak turned out to produce greater travel time savings. It is likely that congestions on other links affected the results of the peak hour analysis. This congested-link analysis showed that the effect of coordinated ramp metering methods can be significant when congested links are locally analyzed. There is no guarantee, however, that the entire system would experience a similar amount of reduction in travel time systemwide, as was seen in the previous sections. Many factors affect the performance of ramp metering and reductions in travel time at one link may be used up by increases in travel time at other links. This simulation analysis of total travel time reflects the difficulty associated with evaluating the overall performance of ramp metering methods.

7.6 Comparison of Fuel Consumption

After travel times of various scenarios were evaluated, the amount of fuel used during the peak hours was analyzed to determine how much fuel savings can be achieved. Fuel consumption data are provided in the WATSim© output for every 15-minute simulation interval. This analysis was done for the same output files as those used for travel time analysis. Note that only the southbound direction was analyzed for the AM peak hour and the northbound direction for the PM peak hour because these are the directions that are congested and receive ramp metering during those hours. Also, the fuel analysis was conducted only for the mainline and used both the base year traffic volume and the future volume with a 20% increase. The analysis was done for the entire 10-mile section.

7.6.1 AM peak hour

Tables 7.19 and 7.20 show the results of the fuel consumption analysis. Negative values mean fuel savings. Hence, in the case of base year volume, the no-meter case used 3,200 gallons of fuel in the AM peak hour in the southbound freeway mainline of the study section of I-15, while the local responsive metering used 3,187 gallons of fuel, resulting in a reduction of 13 gallons in the peak hour. This is not a large difference considering the randomness of simulation. With the increased traffic, fuel consumption goes up because of a larger number of vehicles traveling. Nevertheless, fuel consumption did not decrease significantly for the metering cases as shown in Table 7.20. At the base year volume level, the Seattle Bottleneck algorithm resulted in the highest difference in fuel use; however, at the 20% increase in traffic volume, this algorithm increased fuel use. These small differences are consistent with the results of travel time analyses.

Table 7.19 Comparison of fuel use in the AM peak hour with the base year traffic volume.

Cases	Gallons	Difference (gal)	% Difference
No Metering	3200	[redacted]	[redacted]
Local	3187	-13	-0.40%
Denver	3187	-13	-0.40%
Minnesota	3191	-8	-0.26%
Seattle	3089	-110	-3.45%

Table 7.20 Comparison of fuel use in the AM peak hour with 20% increase in the base year traffic volume.

Cases	Gallons	Difference (gal)	% Difference
No Metering	4246	[redacted]	[redacted]
Local	4209	-37	-0.87%
Denver	4238	-7	-0.18%
Minnesota	4242	-4	-0.08%
Seattle	4252	6	0.15%

7.6.2 PM peak hour

Tables 7.21 and 7.22 show the results of fuel consumption analysis for the PM peak hour. The number of vehicles traveling during the PM peak period is much less than the number of vehicles traveling in the AM peak hour; hence the amount of fuel consumed is smaller for the PM peak hour. Fuel savings as a result of ramp metering turned out to be better in the PM peak hour than in the AM peak hour as shown in the two tables. At both volume levels, ramp metering saved 2% to 3% in fuel use.

Table 7.21 Comparison of fuel use in the PM peak hour with the base year traffic volume.

Main Line Fuel Consumption Comparison

Cases	Gallons	Difference	% Difference
No Metering	2539	[redacted]	[redacted]
Local	2490	-49	-1.93%
Denver	2459	-81	-3.17%
Minnesota	2469	-71	-2.79%
Seattle	2466	-74	-2.90%

Table 7.22 Comparison of fuel use in the PM peak hour with 20% increase in the base year traffic volume.

Main Line Fuel Consumption Comparison

Cases	Gallons	Difference	% Difference
No Metering	3137		
Local	3073	-64	-2.03%
Denver	3082	-54	-1.73%
Minnesota	3069	-67	-2.14%
Seattle	3090	-47	-1.49%

7.7 Analysis of Ramp Travel Times

In addition to the analysis of the 10 mile study segment an analysis of the travel time on the ramp links that are controlled by ramp meters was performed. Only the peak hour for both the AM and PM periods were used in the analysis. Similar to the fuel saving analysis, only the southbound on-ramps were analyzed for the AM peak hour and the northbound on-ramps for the PM peak hour. This is because the southbound on-ramps are metered in the AM peak hour and the northbound on-ramps in the PM peak hour for the study site. Two volume levels (base year volume and 20% increase in the base year volume) were analyzed. Note that there are five on-ramps in each direction.

7.7.1 AM peak hour

Average total travel times (ATTTs) on on-ramps depends upon the level of freedom available for a vehicle to enter the mainline. If a vehicle is impeded from entering the mainline by a ramp meter, the travel times on that ramp will increase. This could counteract the travel time savings achieved by the improvement in the mainline traffic flow. Consequently this analysis was done to determine the increase in travel time experienced by vehicles entering the freeway on meter-controlled ramps. Tables 7.23 and 7.24 present the results of the analysis. The values shown in the tables are the total travel time for the five metered ramps. Obviously, metering increased the travel times on the on-ramp links, by almost 25% to 50% although actual increases may be relatively small. These increases almost counter the travel time savings in the main flow, especially at the base year volume level. At the 20% volume increase level, travel time increases on the ramps are equivalent to 30% to 50% of the travel time savings in the main flow.

Table 7.23 Comparison of on-ramp travel time in the AM peak hour with the base year traffic volume.

Metering Cases	ATTT (hrs)	Difference (hrs)
No Metering	4.98	
Local	6.96	1.98
Denver	6.96	1.98
Minnesota	6.94	1.97
Seattle	7.00	2.02

Table 7.24 Comparison of on-ramp travel time in the AM peak hour with 20% increase in the base year traffic volume.

Metering Cases	ATTT (hrs)	Difference (hrs)
No Metering	5.83	[redacted]
Local	9.84	4.02
Denver	9.83	4.01
Minnesota	9.52	3.70
Seattle	7.67	1.85

7.7.2 PM peak hour

The results of the analysis are shown in Tables 7.25 and 7.26. The northbound on-ramps experience more travel time at both volume levels in the PM peak hour. The amount of increase in travel time on the on-ramps accounts for about 30% to near 100% of the travel time savings in the freeway main line traffic.

Table 7.25 Comparison of on-ramp travel time in the PM peak hour with the base year traffic volume.

Metering Cases	ATTT (hrs)	Difference (hrs)
No Metering	5.96	[redacted]
Local	9.62	3.65
Denver	15.61	9.65
Minnesota	8.99	3.03
Seattle	17.99	12.03

Table 7.26 Comparison of on-ramp travel time in the PM peak hour with 20% increase in the base year traffic volume.

Metering Cases	ATTT (hrs)	Difference (hrs)
No Metering	18.21	[redacted]
Local	32.40	14.20
Denver	42.16	23.96
Minnesota	21.12	2.91
Seattle	37.75	19.55

It seems that the Seattle Bottleneck algorithm is most restrictive, followed by the Denver Helper algorithm and the Minnesota Zone algorithm. The local responsive metering is somewhere between the two extremes.

7.8 Summary

The simulation analysis in this chapter showed that ramp metering does help stabilize the overall level of service of traffic flow on the freeway. In terms of the reduction of travel time, ramp metering produced mixed results for the study site. Spatial and temporal factors affected the results of the analysis. For the study section, the delay on metered on-ramps increased to the level where the savings in total travel time on the freeway might be cancelled out by the increased delay on the metered links.

The reduction in travel time when summarized for the entire study section and for the one hour peak period, however, was small for the freeway section studied. There was practically no difference in the AM peak hour and a 1 to 2% travel time savings in the PM peak hour for both the base year traffic and the case with a 20% increase in traffic volume. There are several reasons why savings in total travel time turned out to be smaller than expected for this freeway section. One reason for the small reduction in travel time due to ramp metering is that only a few locations of this facility are really congested and the duration of heavy congestion is relatively small, say about 30 minutes at most at present for both morning and evening. Another reason is that the most congested location in the morning just upstream of the diversion from I-15 to I-215 is not metered because it is a freeway-to-freeway diversion. The 15-minute peak interval analysis resulted in a similar conclusion.

The analysis of congested links for each 15-minute interval of the peak one hour for both AM and PM peak periods, however, showed dramatically different results. Congested links were found near the 500 South interchange in both AM and PM peak periods. In a 15-minute peak interval in the AM peak hour the Denver Helper algorithm achieved about a 30% travel time reduction on one link and the Seattle Bottleneck algorithm achieved about a 16% travel time reduction on the same link. The local responsive and the Minnesota Zone algorithm methods achieved an almost 10% reduction in travel time during one 15-minute interval. As mentioned earlier, the study section has only two congested segments, one near 500 South and the other at the diversion point between I-15 South and I-215 West. Since the diversion point is not metered, the travel time savings achieved on congested links near 500 South are averaged out both temporally and spatially when analysis is done for the one hour peak period and for the entire study segment. The analysis of congested links in the PM peak resulted in a relatively small reduction in travel time—up to about 2%.

The fuel consumption analysis showed that the amount of fuel saved for the AM peak hour was fairly low compared to the PM peak hour. Fuel savings were minimal for the AM peak hour – about 1% or less, while fuel savings for the PM peak hour were 2% to 3%. All ramp metering methods tested in the study resulted in similar values for both volume levels tested; however, the Denver Zone algorithm seems to produce the best results for the study section.

Whenever ramp metering is implemented the entry of on-ramp vehicles to the freeway main flow will be restricted. The analysis of metered on-ramps showed how restrictive ramp metering could be to on-ramp vehicles. The Seattle Bottleneck algorithm seemed to be the most restrictive among the metering methods tested. With the Seattle Bottleneck algorithm, the amount of increase in travel time to the vehicles on the metered on-ramps was almost equivalent to the travel time reduced for the freeway main flow.

Practically all the tested metering methods increased on-ramp travel time (that is, delay), offsetting 30% to almost 100% of the total travel time saved for the freeway main flow.

Other benefits of ramp metering include reduced accident potential, which cannot be easily assessed by any traffic studies. Reducing the chance of having LOS F contributes to stabilization of traffic flow, however, which will eventually contribute to the reduction of accident potential. All the ramp metering methods tested in this study would help the traffic engineer achieve this goal, as the density charts in this chapter demonstrated. Another positive effect of ramp metering is that vehicle entry from on-ramps can be regulated by ramp metering, reducing the possibility that a surge of vehicle will enter from the on-ramp into the freeway main flow. Despite the fact that ramp metering does provide such benefits, it is difficult to place dollar values on these improvements.

8. CONCLUSIONS

Based on the findings from the literature search, simulation analysis, and field observations, the following conclusions are made. The conclusions drawn from the simulation analysis were made based on the analysis of a 10-mile section of I-15 just north of Salt Lake City between North Salt Lake (Beck St. interchange) and Farmington (Glover Lane interchange). The southbound direction has typically two congested locations—near 500 South and the diversion to I-215 West—in the AM peak. The diversion section is not metered because it is a freeway-to-freeway diversion. The northbound direction typically has congestion at one place—just south of 500 South in the PM peak period. The real peaking of traffic occurs generally for about 30 minutes in the study area.

- Other researchers have shown that ramp metering helps stabilize the level of service of traffic flow during the peak hour. However, traffic control and geometric factors affect the effectiveness of its use. Mixed results were reported regarding the performance of coordinated ramp meter methods.

- Field observations conducted in 2000 and 2001 at the study site showed that the level of service of the studied section of I-15 would rarely reach LOS F during the AM and PM peak periods. The only location where the level of service seemed to reach LOS E was during the PM peak period just north of the 2600 South interchange (that is, south of the 500 South interchange). This congestion was created by a queue spilling over from the signalized intersection at the bottom of the 500 South off-ramp into the main traffic flow on the freeway, blocking the vehicles wanting to get off at the 500 South off-ramp. It is necessary to analyze the causes of congestion on the freeway and identify where bottlenecks that might eventually affect the level of service of the freeway would take place. If bottlenecking occurs outside the freeway main flow, such bottlenecks need to be corrected in order to maximize the capacity of the freeway.

- With the base year volume (reflecting the 1998 volume level), none of the ramp meter methods evaluated in the study (local responsive, Denver Helper, Minnesota Zone, and Seattle Bottleneck algorithms) would significantly out-perform the no-metering control because the quality of traffic flow rarely degrades to level of service F, both in the AM and PM periods. The level of service of the studied section of I-15 in simulated models would range from level of service B to level of service D, rarely reaching level of service E. This was confirmed during the field observations conducted in the early stages of the study.

- With an increase in traffic volume, ramp meters begin to show their effectiveness. With a 20% increase in traffic in the system, the level of service on freeways deteriorated and at some locations it reached E and F. Three types of travel time analysis were done: peak hour analysis for the entire 10-mile section, peak 15-minute interval analysis for the entire 10-mile section, and congested link analysis for each 15-minute interval of the peak hour. All ramp meter algorithms evaluated showed some improvements and were able to improve level of service at locations where level of service F is recorded without ramp metering. However, savings in travel time on the freeway were smaller than the level expected. There was practically no difference in travel time in the AM peak hour and a 1 to 2% reduction in travel time in the PM peak hour for both the base year volume and the 20% increase in traffic volume. This small gain most likely was attributed to the fact that real congestion took place only at a few locations: just north of the I-215/I-15 junction and near 500 South in the AM and PM peaks. Also the savings in travel time was averaged out spatially and temporally. The 15-minute/entire section analysis resulted in similar results—practically no difference in the AM 15-minunte peak intervals and a 2% to 4% reduction in total travel time for the PM 15-minute peak intervals when the traffic volume was increased by 20%. The analysis on congested links, however, revealed that large savings can be achieved in a 15-minute peak interval for congested links. In the AM peak period, the Denver Helper algorithm achieved about a 30% reduction in travel time at one congested link compared to the no-metering while the Seattle Bottleneck algorithm achieved a 16% reduction in travel time for the same congested link. The local responsive metering and the Minnesota Zone algorithm were able to reduce travel time for the upstream link of the congested links by about 10% in the same 15-minute time interval. Unlike the AM peak, the analysis on congested links for the PM peak period did not show a large reduction in travel time—only about 2% in one congested link. The simulation analysis revealed the difficulty in precisely measuring and comparing the benefits of various ramp metering methods because of the number of factors affecting the performance of the study section.

- In order to further evaluate the performance of ramp metering algorithms, a bottleneck was created at the intersections on Parrish Lane. When the traffic volumes in the system were increased by 20% from the base 1998 volume, the off-ramp traffic flow formed a queue extending from the bottleneck and spilling into the freeway main flow. The local responsive, Denver Helper, and Minnesota Zone ramp meter algorithms were not able to deal with the off-ramp congestion. The Seattle Bottleneck algorithm, on the other hand, prevented this from happening, creating its own problem. Freeway entry became too restrictive such that at one location the queue that spilled over from the on-ramp completely blocked the intersections on nearby surface streets.

- With a 40% increase in traffic volume, signalized intersections at the end of off-ramps produced bottlenecks at multiple locations. It was apparent that the section of I-15 in the study area had more capacity than the signalized intersections at off-ramps. Queues created at the signalized intersections at off-ramps quickly spread into the freeway main flow. Until the capacity of intersections on nearby surface streets are increased, the maximum volumes on the freeway will not be achieved.

- The fuel consumption analysis reflected the travel time analysis; the amount of fuel saved by the studied ramp meter methods was fairly small—about 1% or less in the AM peak hour and 2% to 3% in the PM peak hour.

- The results of an analysis of metered on-ramps showed that travel times on the metered on-ramps increased. Depending on the metering methods, the increase in the total travel time on metered on-ramps was equivalent to 30% to almost 100% of the total travel time saved for the freeway main flow in the worst case.

- Overall, the local-responsive ramp meter control performed as effectively as the three coordinated ramp meter control methods tested. The Denver Helper algorithm was the next best. The Minnesota Zone and Seattle Bottleneck algorithms had inconsistent performances.

As mentioned at the beginning of this chapter, the reduction in total travel time for the 10-mile section analyzed in the simulation study was relatively small compared to what has been reported by other studies. However, this does not mean that ramp metering would be ineffective in the Wasatch Front region. Physical and traffic characteristics of the section affect the effectiveness of ramp metering. In the studied 10-mile section, one of the major congested segments at the I-215 West diversion point was not metered because it is a freeway-to-freeway diverging point. Congestion at this segment affects the performance of upstream segments. Other sections of freeway in the Wasatch Front may have congested segments close to each other, in which case the coordinated ramp meter methods may behave differently.

Other impacts are difficult to place monetary values on them. Reducing the level of service from F to E or D helps stabilize traffic flow, which reduces accident potential at merge locations on the freeway. All the ramp meter methods tested in this study have a potential for improving safety at merge areas in this way. Also, when an incident takes place in the freeway main flow, ramp metering can be used to greatly reduce the amount of entering vehicles and help shorten the duration of post-accident congestion.

In summary, various conditions of the study site affected the results of the study. Although the local-responsive metering and Denver Helper algorithm seemed to be best suited for the study site, the analysis results were not definitive. Additional work is needed to refine traffic projects, particularly for ramp volumes, evaluate the effect of capacity levels at or around the freeway, evaluate the benefits of ramp-metering for accident reduction or incident clearance and recovery, and evaluate the benefits of correcting surface street bottlenecks on the overall performance of freeway traffic flow.

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9. RECOMMENDATIONS

Based on the results of the study, we offer the following recommendations:

- Ramp metering helps reduce travel time and stabilize the level of service at critical points on the studied section of I-15, although overall travel time reduction was less than expected. Since the local responsive metering is as good as the three coordinated metering methods tested in the study, it is recommended that UDOT continue using the local responsive system until coordinated ramp metering algorithms' cost effectiveness reaches a level acceptable to UDOT. A large reduction in travel time at congested links may be averaged out when an analysis is made for an entire study section and a peak hour. This is especially true when the study section is long and the duration of severe congestion lasts less than an hour.

- Should UDOT decide to choose a coordinated ramp meter control immediately, the Denver Helper algorithm would be the best among the three coordinated ramp meter controls tested for the study site because this method functions as a local responsive metering until the level of service reaches a certain predetermined level where the Helper algorithm is activated. The Minnesota Zone and Seattle Bottleneck algorithms behaved more inconsistently than the Denver Helper algorithm at some locations at the study site.

- Capacities of surface streets and intersections near the freeway interchanges need to be evaluated for potential bottlenecks and improvements made. Freeway or ramps do not supply more traffic to the freeway than the nearby streets and intersections can accommodate; similarly, freeway off-ramps cannot discharge traffic more than the nearby streets and intersections can handle. The latter case is more serious than the former because queues created on off-ramps may spill into the freeway main flow and completely block the freeway. The former case simply results in the underutilization of the freeway.

- Corridor management tools encompassing both freeway ramp meter control and surface street signal control need to be developed to maximize the use of freeway capacity. Congestion on the freeway caused by the queue spilling over from off-ramps due to the bottleneck problems of the nearby surface street intersections may not be able to be resolved simply by freeway on-ramp traffic controls.

- In order to assess the effect of coordinated ramp metering algorithms on the entire I-15/I-215/I-80 system in the Salt Lake City metropolitan area, it is recommended a simulation model be developed consisting of the entire freeway and major arterials connecting to the freeway system. This study used a 10-mile stretch of I-15. Though its simulation results provide a valuable insight into the evaluation of coordinated ramp meter controls, the full potential of the coordinated ramp meter controls may not be known until a full-scale simulation model for the Wasatch Front freeway system is analyzed. For instance, the Minnesota Zone algorithm makes adjustments between the adjacent zones; however, this study considered only a single zone due to the size of the section studied. Once a simulation model of the entire system is built, it can be used not only for testing the effect of coordinated ramp meter controls on the entire system, but also for other what-if analyses, including incident management, special event traffic management, and emergency evacuation scenarios analyses. Also recommended is to improve traffic projections, particularly for ramp volumes by requesting the refinement of regional demand forecasting models.

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APPENDICES

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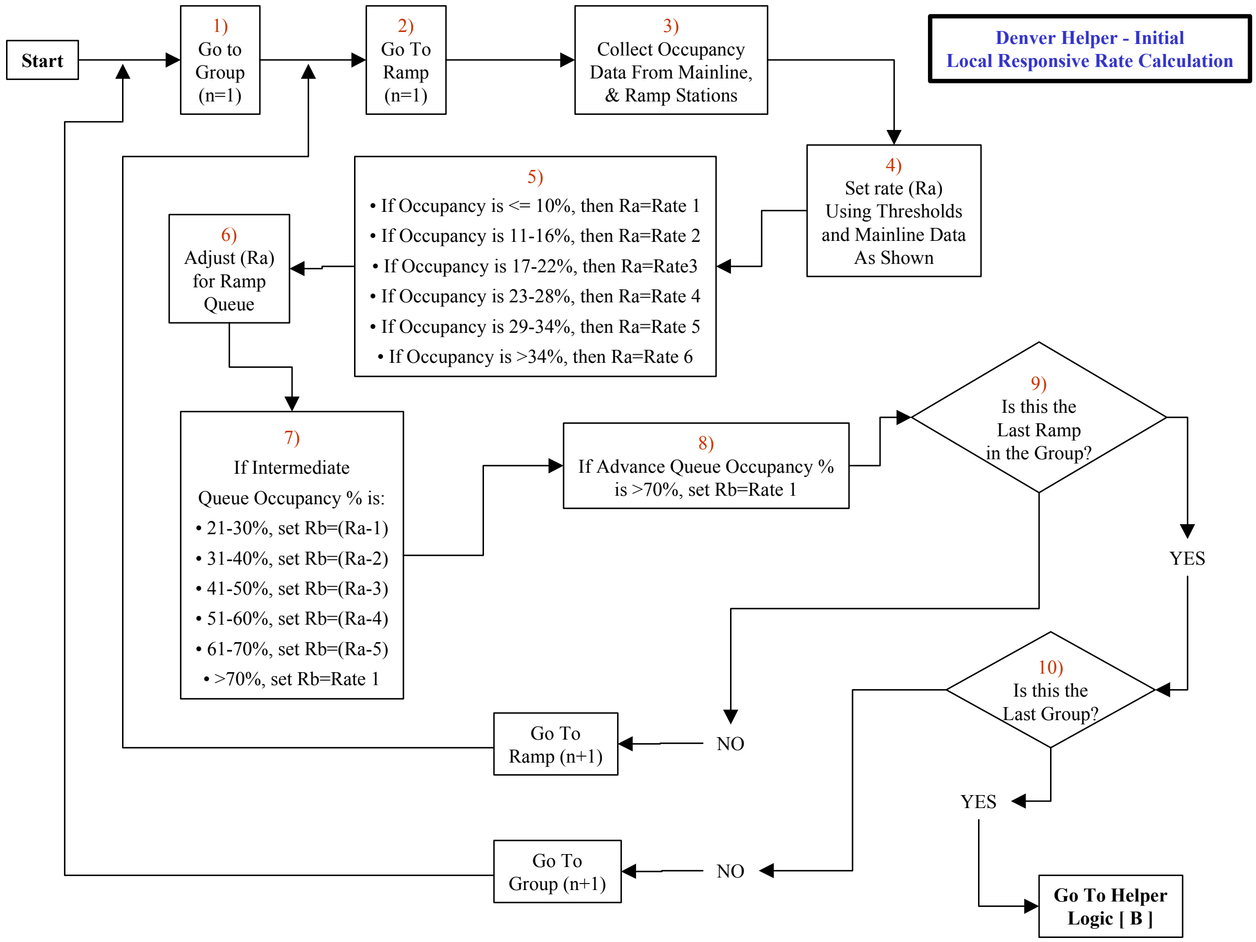
APPENDIX A - DENVER HELPER ALGORITHM APPLIED TO THE STUDY SITE

(The figure and text complement one another—refer between the two accordingly.)



Initial Traffic Responsive & Queue Override Calculation

The Denver algorithm calculates a rate for each ramp in 3 separate ways: as a local responsive rate at each ramp, as an adjusted rate which accounts for queue lengths at each ramp, and as a system-wide algorithm. The calculation for all three is a stepwise process and iterates once every 20 seconds, identical to the polling rate of the system detectors.

Step 1: For algorithm application, metered corridors are predefined as a series of groups of ramps, with each group defined by an upstream free-flow point and a downstream bottleneck. Groups may be of any size, but should contain multiple ramps for an effective application of the Helper algorithm. Due to the size of the Davis County corridor study area and the small number of ramps available, the entire corridor will be considered one group; all southbound ramps are in one group, and all northbound ramps are in one group.

Step 2: Within the group, the ramps are identified in numeric order in the direction of travel. This is not required, but this convention will be followed through the description of the algorithm to assist in its description. The ramps being considered in this study are the following:

AM (Southbound):

1) Glover Lane	2) Parrish Lane	3) 400 North	4) 500 South	5) 2600 South

PM (Northbound)

6) Beck Street	7) 2600 South	8) 500 South	9) Hwy 89	10) Parrish Lane

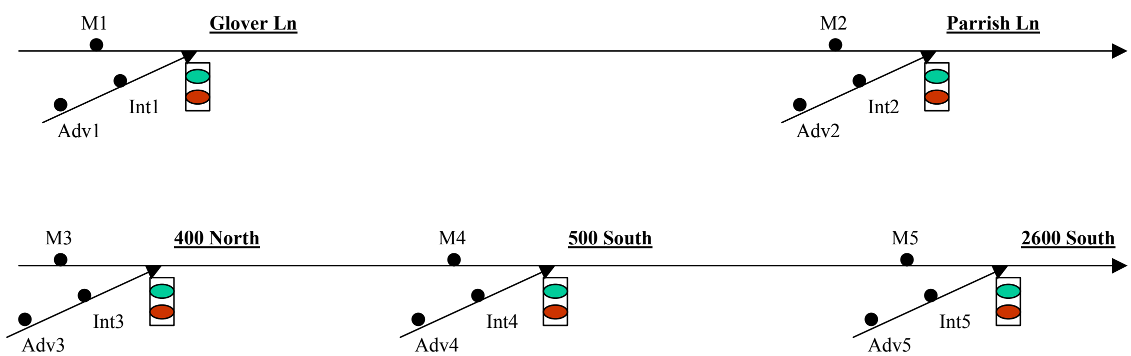
Step 3: To begin the calculations, data must be collected from the corridor at each detector station of interest. The maps and tables below identify, for the Helper Algorithm, the detector sites where data are collected within the study corridor, the name/purpose for its collection, and which of the ramps from Step 2 it should be associated with.

(M) indicates the upstream mainline detector station nearest each ramp entrance.

(Adv) indicates the advance queue detector station—if available—at the head of each ramp.

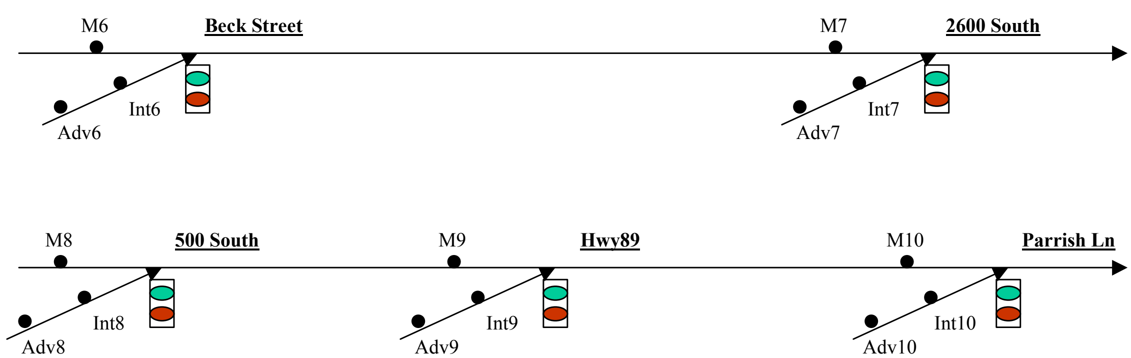
(Int) indicates the intermediate queue detector station—if available—in the middle of each ramp.

Denver Helper Algorithm - AM Detector Stations



Map ID	M1	Adv1	Int1	M2	Adv2	Int2	M3	Adv3	Int3	M4	Adv4	Int4	M5	Adv5	Int5
WATsim ID															

Denver Helper Algorithm - PM Detector Stations



Map ID	M6	Adv6	Int6	M7	Adv7	Int7	M8	Adv8	Int8	M9	Adv9	Int9	M10	Adv10	Int10
CORSIM ID															

Step 4: The local responsive rate is calculated using occupancy values taken from the mainline detector station just upstream of the ramp merge area at each interchange—the (M#) detector. The values from all lanes are averaged to produce a single occupancy percentage for the station, and based on these values a local metering rate (Ra) is assigned as one of (6) possible values using the relationships and values shown in the table below.

Step 5: The local metering rate relationships are based on the recommended values given in *The Traffic Control Systems Handbook (Feb96), pg.4-23*. These have been adjusted to conform to the general metering-rate limits of 4-second cycle minimums and 15-second cycle maximums, which are UDOT policy. The values shown assume a green-time of 1.5 seconds and no yellow lamp—also UDOT policy.

Rate ID	**Occupancy (%)**	**Metering Rate (vpm)**	**Red-Time (seconds)**	**Cycle Time (seconds)**
Rate 1	</= 10	15	2.5	4
Rate 2	11 – 16	10	4.5	6
Rate 3	17 – 22	7.5	6.5	8
Rate 4	23 – 28	6	8.5	10
Rate 5	29 – 34	5	10.5	12
Rate 6	>34	4	13.5	15

Step 6: Once a local-responsive metering rate is calculated, the effect of any ramp queue which may exist is accounted for at each site. This is done by adjusting the value of (Ra) calculated in accordance with the measured value of occupancy at the detector stations on each ramp. The purpose of these adjustments is to clear excessive ramp queues and prevent the queue from backing onto the surface street.

Step 7: For the intermediate detector station (where available):

Based on the occupancy value measured, the rate level calculated for (Ra) is decreased by the number of levels indicated in the figure. This adjusted value is then called (Rb). (That is, if Ra=Rate 5, and the intermediate detector occupancy was measured to be 45% over the past 20 seconds, then according to the table shown in the figure, Rb for that ramp is [Rb=Ra-3 rate levels = Rate 4].)

CoDOT uses only one ramp queue detection station for their operation of this algorithm, and the methodology shown here for the intermediate queue adjustment corresponds to their procedure. However, UDOT ramps will often use both an intermediate and an advanced detection station. To account for this additional input, an additional adjustment will be added here to respond to situations where an advance queue detection station may be available.

Traditionally there are two methods used to clear ramp queues that threaten surface street free-flow. The first is to suspend metering for one full interval by giving a solid green light to traffic at the meter and "flush" the ramp. While this effectively clears the ramp, it sends a solid platoon into heavy mainline traffic, which tends to induce a cyclic process; slow mainline causes ramp queue, the ramp queue causes flushing, flushing further degrades mainline traffic, and so on.

The second method is to implement the least restrictive metering rate for a full interval. This is a compromise solution—with heavy surface street flows, backing may reach onto the surface street in spite of this, while with heavy mainline flows, the additional influx may induce some cyclic response. Despite these issues, this alternative maintains a metered flow onto the mainline;, and simply breaking up platoons in this manner is known to constitute the majority of the benefit to be derived from ramp metering. This and the lesser impact on mainline operations relative to the first alternative are what have been added to the algorithm described herein.

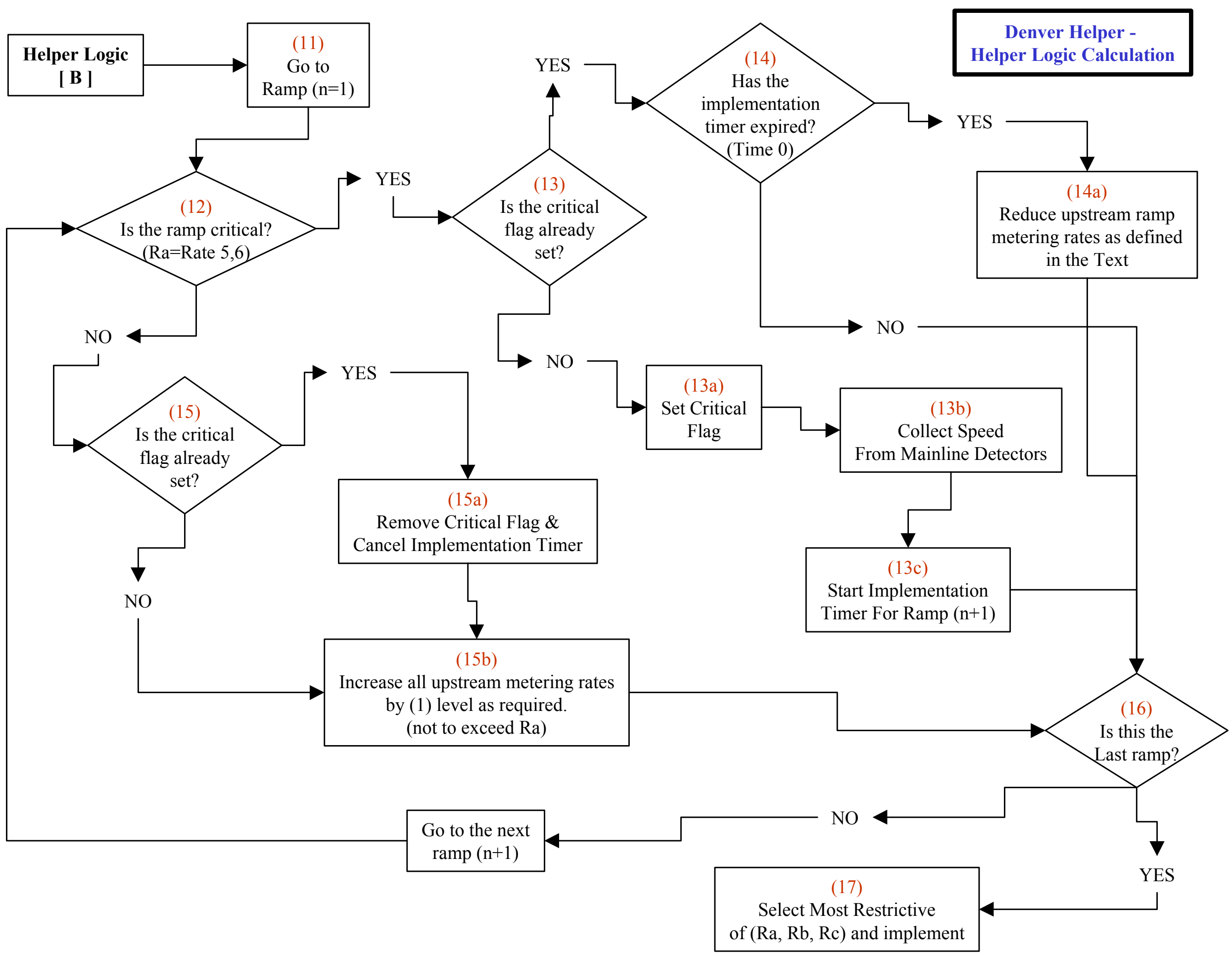
Step 8: For the advanced detector station (where available):

This is a binary operation, as shown in the figure. If the occupancy value measured at the advanced detection station is greater than 70% (this value is based on that identified within the intermediate adjustment methodology), then (Rb) is set to Rate 1, regardless of intermediate detection adjustments.

Step 9 / 10: These local-responsive and queue-override calculations are iterated for each ramp in each group, from (1) to (n). This produces a value for (Ra) at each ramp, which is then used in the Helper logic to define critical states. Values for (Rb) may or may not be calculated, depending on the ramp queue at each site. If not calculated, (Rb) is set to a null value. Once all ramps in all groups have completed this process, the algorithm moves into the systemwide Helper logic rate calculation.

Helper Logic Calculation

(The figure and text complement one another—refer between the two accordingly.)



The basis for the Helper logic is the existence of a "critical state" at one or more ramps, defined by a ramp having calculated (Ra = Rate 5 or 6) in the local-responsive calculation process. A "critical flag" is used to indicate to the algorithm that the ramp is currently critical.

Step 11: As before, the algorithm progressively examines each ramp in the system, by groups, in applying the Helper logic.

Step 12: The Helper logic begins by examining each ramp in turn to see if it is critical or not. Ramps where (Ra) has been calculated as Rate 5 or 6 are defined as critical. Several different scenarios may exist at this point:

Step 13: If the ramp *is* critical, the algorithm then looks to see if it was critical during the past iteration by looking to see if the critical flag is already set.

Step 13a: If the critical flag was *not* set during the past interval, then the ramp has just become critical for the first time and the critical flag is now set by the program.

Step 13b: To begin the Helper logic, the algorithm requires a speed measurement at the ramp to know at what value the implementation timer should be set. This speed is taken from the mainline detector just upstream of the ramp entrance (M#).

Step 13c: Using the measure speed value, the algorithm then assigns a value to the implementation timer using the relationships and values shown in the tables below, and the program begins timing.

The following tables depict distances and values to be input into the implementation timer for all ramp locations in the Davis County corridor. *For example, if 500 South were critical during the AM period, and the average speed at (M4) was 33mph, then the upstream ramp (n+1) would be 400 North and the implementation timer would be set to (67 seconds).*

AM / Southbound Implementation Timer Table

Upstream Site	Distance	0-10mph	11-20mph	21-30mph	31-40mph	41-50mph	51-60mph	61-70mph
2600 South to 500 South	1.55 miles	1116 sec	372 sec	223 sec	160 sec	124 sec	102 sec	86 sec
500 South to 400 North	.65 miles	468 sec	156 sec	94 sec	67 sec	52 sec	43 sec	36 sec
400 North to Parrish Lane	1.9 miles	1368 sec	456 sec	274 sec	195 sec	152 sec	124 sec	105 sec
Parrish Ln to Glover Lane	3.2 miles	2304 sec	768 sec	461 sec	329 sec	256 sec	209 sec	177 sec

PM / Northbound Implementation Timer Table

Upstream Site	Distance	0-10mph	11-20mph	21-30mph	31-40mph	41-50mph	51-60mph	61-70mph
Glover Ln to Parrish Lane	3.2 miles	2304 sec	768 sec	461 sec	329 sec	256 sec	209 sec	177 sec
Parrish Lane to Hwy 89	1 mile	720 sec	240 sec	144 sec	103 sec	80 sec	66 sec	56 sec
Hwy 89 to 500 South	1 mile	720 sec	240 sec	144 sec	103 sec	80 sec	66 sec	56 sec
500 South to 2600 South	1.55 miles	1116 sec	372 sec	223 sec	160 sec	124 sec	102 sec	86 sec
2600 South to Beck Street	2.5 miles	1800 sec	600 sec	360 sec	258 sec	200 sec	165 sec	140 sec

Step 14: If the critical flag *was* set during the past interval, then the ramp has been critical for some amount of time in the past. The algorithm must now determine if the previously set implementation timer has expired, prior to proceeding. If the timer has *not* expired, then the algorithm proceeds on to the next ramp (Step 16).

Step 14a: If the timer has expired, then the Helper logic must be applied to the upstream ramps. This application is based on how long the timer has been expired, as defined in the table below. This table depicts the rate reductions to be applied to each upstream ramp at each time interval. For this process, the unit of Time is considered to be the calculation interval (i.e., Time 0 is the interval in which the implementation timer is seen by the program to have expired, Time 1 is the next interval after that, etc.).

Time	Ramp (n+1)	Ramp (n+2)	Ramp (n+3)	Ramp (n+4)	Ramp (n+5)	Etc.
Time 0	Rc = (Ra – 1 Rate)					
Time 1	Rc = (Time 0 Rate – 1 Rate)	Rc = (Ra – 1 Rate)				
Time 2	Rc = (Time 1 Rate – 1 Rate)	Rc = (Time 1 Rate – 1 Rate)	Rc = (Ra – 1 Rate)			
Time 3	Rc = (Time 2 Rate – 1 Rate)	Rc = (Time 2 Rate – 1 Rate)	Rc = (Time 2 Rate – 1 Rate)	Rc = (Ra – 1 Rate)		
Time 4	Rc = (Time 3 Rate – 1 Rate)	Rc = (Time 3 Rate – 1 Rate)	Rc = (Time 3 Rate – 1 Rate)	Rc = (Time 3 Rate – 1 Rate)	Rc = (Ra – 1 Rate)	
Etc.	Etc.	Etc.	Etc.	Etc.	Etc.	Etc.

This process is continued as shown here, iterating for each interval so long as Ramp (n) is critical, until all ramps in the system are either operating at the most restrictive rate or Ramp (n) is no longer critical. Upon completion of the current Time Interval adjustment, the algorithm proceeds to the next ramp (Step 16).

Step 15: If the ramp is *not* critical, the algorithm looks to see if it was critical during the past iteration by looking to see if the critical flag is already set. If the critical flag was NOT set during the past interval, then the ramp was not being impacted by the Helper logic and the algorithm moves on to consideration of the next ramp or group (Step 16).

Step 15a: If the critical flag WAS set during the past interval, then the ramp was previously critical, and the Helper Logic rate reductions which have been applied need to be removed from the upstream ramps.

- First, the program removes the critical flag from Ramp (n).
- Second, the program cancels the implementation timer if it is currently running for this ramp.

Step 15b: The program returns the ramp metering rates at all upstream ramps to noncoordinated operation by increasing the rate level at upstream ramps one level per interval until they are equal to (Ra). This logic interates each interval until all ramps impacted by the Helper Logic are returned to noncoordinated operation. Following this adjustment during each interval, the algorithm then proceeds to the next ramp (Step 16).

Step 17: This logic iterates through all ramps and groups each interval. As a result, many ramps may have multiple metering rates assigned to them from multiple downstream critical ramps at different stages of logic implementation. The final metering rate for each ramp is taken as the most restrictive (i.e., highest rate) from among the three variables calculated—Ra, Rb, Rc.

As an addendum, if (Rb) is calculated at all, then this value must be used by the algorithm, period. Taking the most restrictive rate will never select (Rb), because it is, by definition, less restrictive than (Ra). Summary: If (Rb) is non-null in value, use (Rb) as the local rate. Continue to calculate (Rc) using (Ra) as normal.

APPENDIX B – MINNESOTA ZONE ALGORITHM APPLIED TO THE STUDY SITE

The Zone algorithm focuses primarily on a volume-balancing zone-based metering control, with area-of-influence occupancy-based control (a variation of local traffic responsive) employed as a secondary calculation to respond to more localized impacts near specific ramps. These two algorithms are run in parallel for all sites, and the most restrictive timing recommendation is used as the metering rate value for the following interval.

Zone Algorithm Rate Calculation

Prior to outlining the metering rate calculation methodology, the basis for the operation of the Zone algorithm will be set forth, both to familiarize the reader and to define terms.

The controlling equation for the Zone algorithm is a balance of inflow volumes and outflow volumes from a freeway section. A section is generally 3–6 miles long in Minnesota applications, and is defined on the upstream end by a free-flow portion of freeway and on the downstream end by a controlling bottleneck location. Sections may (and do) have multiple on and off ramps, freeway-to-freeway connections, or minor bottleneck locations.

For both the NB and SB Davis County simulation, the entire length of the corridor will be defined as a single section, due to the close proximity of the ramps and lack of "free flow" portions within the study corridor.

The generalized Zone equation is as follows:

$$[\ \mathbf{A + U + M + F = X + B + S}\ ] \qquad \mathbf{(1)}$$

where

A = Upstream mainline volume entering the section (measured)

U = Total of the unmetered entrance ramp volumes within the section (measured)

M = Total of the metered entrance ramp volumes within the section (controlled constant)

F = Total of the metered freeway-to-freeway entrance volumes within the section (controlled constant)

X = Total of the off-ramp volumes within the section (measured)

B = Downstream section end bottleneck capacity (constant)

S = Space available within the zone (computed/measured)

Rearranging variables to solve for the output values of (M) and (F):

$$[\ \mathbf{(X + B + S - A - U) = (M + F)}\ ] \qquad \mathbf{(2)}$$

The algorithm calls for the user to use "target" values to solve equation (2) prior to implementation, and through so doing, use known peak-hour historical volumes to define fixed values for (Mt) and (Ft), which are then applied by the algorithm in rate calculation. The following table of values was collected using 1998 UDOT volume counts at stations within the study corridor.

Variable	Definition	AM (SB) Peak Hour Volume		AM (SB) 5-minute Volume (Target Value)	PM (NB) Peak Hour Volume		PM (NB) 5-minute Volume (Target Value)
Bt	Bottleneck Capacity Volume	**4400** (S of Beck - 2 lanes)		**367**	**6600** (N of Glover Ln - 3 lanes)		**550**
At	Upstream Mainline Volume	**4000** (N of Glover)		**333**	**2200** (@ Beck St.)		**183**
Ut	Unmetered Entrance Volume	**0** (no unmetered ramps)		**0**	**3300** (I215 EB)		**275**
Mt	Metered Entrance Volume	**5150**		**429**	**4170**		**348**
		**1000	Glov	**83**	1450	Beck	**121**
		850	Prsh	**71**	560	2600	**47**
		**600	400N	**50**	460	500s	**38**
		**1200	500S	**100**	850	Hw89	**71**
		**1500	2600	**125**	850	Prsh	**71**
Ft	Metered Freeway Volume	**0** (no metered freeways)		**0**	**0** (no metered freeways)		**0**
St	Space Available Volume	**0** (target condition is no space available)		**0**	**0** (target condition is no space available)		**0**
Xt	Exit ramp Volume	**7730** (Parrish = 320) ** (Hwy89 = 300) ** (500S = 1200) ** (2600S = 300) (Center = 60) (I215 = 3800) ** (Beck = 1750)		**644**	**3200** (2600S = 1150) (500S E&W = 600) (400N = 550) (Parrish = 600) ** (Farmington = 300)		**267**

** Indicates estimated value

Actual target value calculation of (Mt) and (Ft) is accomplished using 5min volume numbers, as done in MnDOT. The zone equation as expressed in (2) is balanced between the sum of (Mt + Ft) and the sum of (X + B + S – A – U), with variations in this balance being made up through adjustments in the value of (Mt). As UDOT policy is currently not to meter freeway-to-freeway connections, (Ft) goes to zero immediately, and solving this equation for both the AM and PM periods yields the following:

- <u>AM Balance</u>:

  [(Mt = 429) = (X+B+S−A−U = 644 + 367 + 0 − 333 − 0)] ---> [429 < 628]

  The equation is thus out of balance by (47%). Adjusting (Mt) values at each ramp from the values shown above by (47%) to compensate for this difference yields the following values (which sum to the zone value of Mt=628):

  Glover Ln (Mt = 122)

  Parrish Ln (Mt = 104)

  400 North (Mt = 73)

  500 South (Mt = 146)

  2600 South (Mt = 183)

- <u>PM Balance</u>:

  [(Mt = 348) = (X+B+S−A−U = 267 +550 + 0 – 183 – 275)] ---> [348 < 359]

  The equation is thus out of balance by (3%). Adjusting (Mt) values at each ramp from the values shown above by (3%) to compensate for this difference yields the following values (which sum to the zone value of Mt=359):

  Beck St (Mt = 124)

  2600 South (Mt = 48)

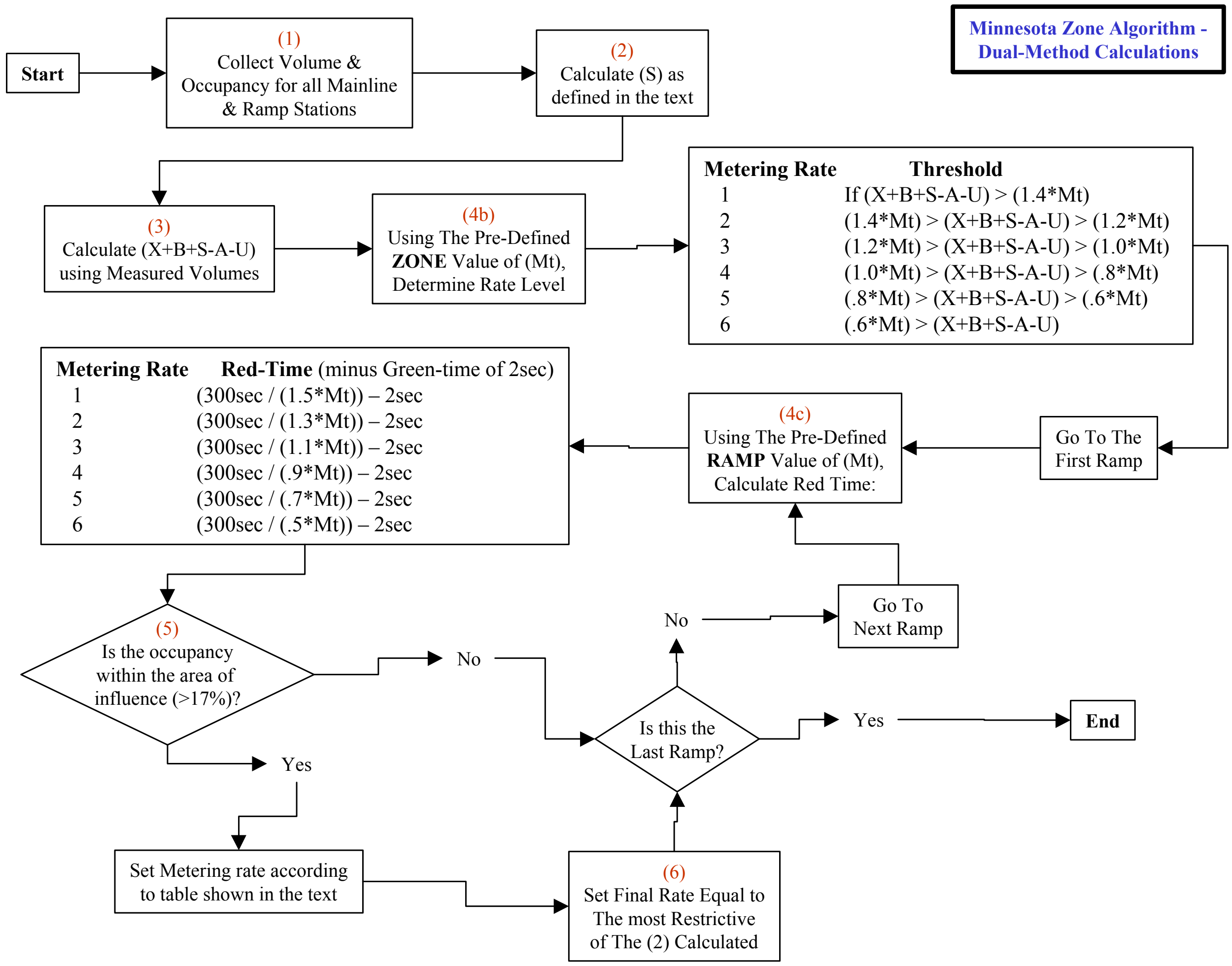
500 South (Mt = 39)

Hwy 89 (Mt = 73)

Parrish Ln (Mt = 73)

Once this calculation has been run and target values found for both (Mt) and (Ft), they are set as predefined constants and entered as such into the algorithm, which may then run.

(The figure and text complement one another—refer between the two accordingly.)



Step 1: This algorithm measures mainline volumes on a 30-second cycle, while the remaining variables are measured on a 5-minute cycle. All variables—including mainline volumes—are used in equation calculations as 5-minute volumes (requiring some conversion and extrapolation), though the algorithm is iterated every 30 seconds. The maps and tables below indicate the required detectors from which data are collected to satisfy the algorithm.

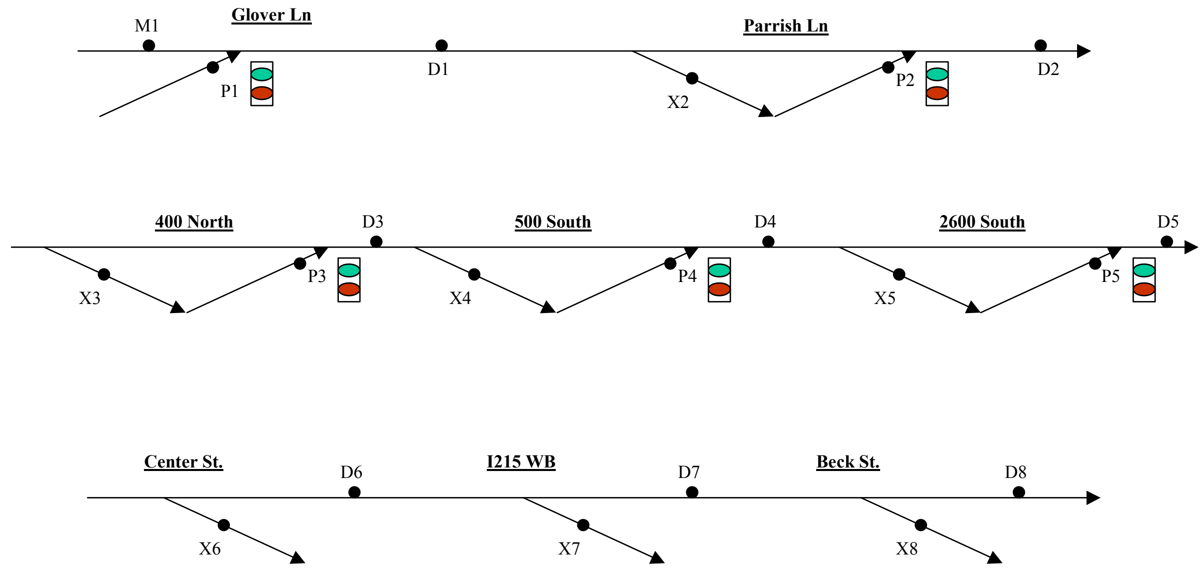
(M) indicates the upstream mainline detector station nearest the ramp shown.

(D) indicates a downstream detector between the interchanges shown.

(P) indicates the passage detector loops located just past the stop bar on each entrance ramp.

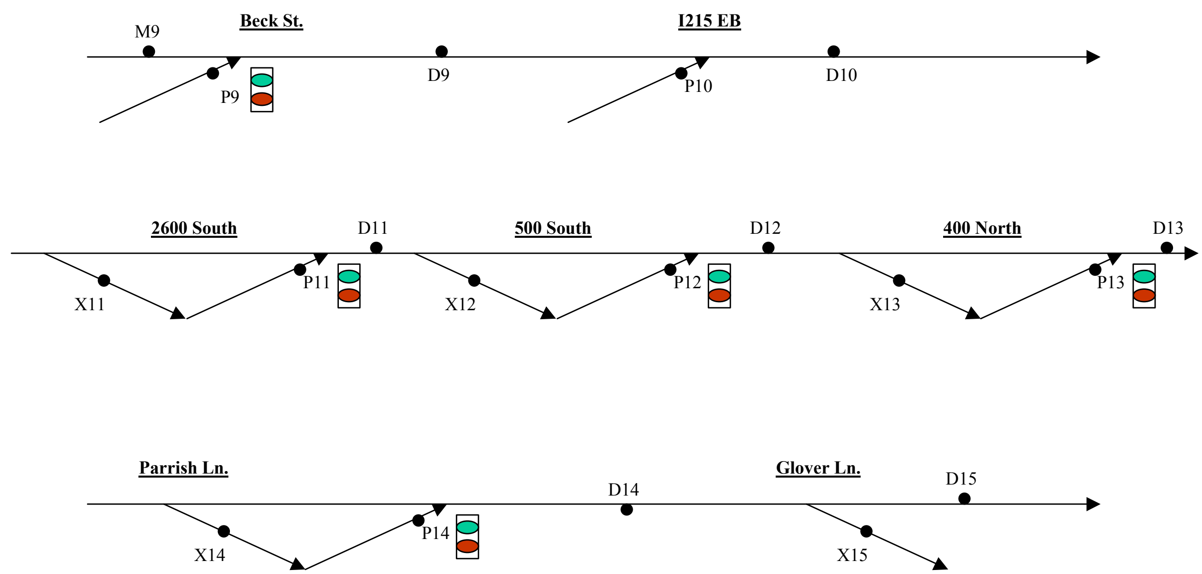
(X) indicates the off ramp detector loops on each exit ramp.

Minnesota Zone Algorithm - AM Detector Stations



Map ID	M1	P1	D1	X2	P2	D2	X3	P3	D3	X4	P4	D4
CORSIM ID												
Map ID	X5	P5	D5	X6	D6	X7	D7	X8	D8			
CORSIM ID												

Minnesota Zone Algorithm - PM Detector Stations



Map ID	M9	P9	D9	P10	D10	X11	P11	D11	X12	P12	D12
CORSIM ID											
Map ID	X13	P13	D13	X14	P14	D14	X15	D15			
CORSIM ID											

Step 2: The second step, once all data have been collected, is to calculate the value of (S) for the given time interval. This is done by subtracting the real-time measured volume in the zone from the predefined capacity of the zone (based on 32veh/mile).

The predefined density capacity of the study corridor is calculated as shown below:

AM Capacity:

[Capacity = (32veh/lane-mile)*(7miles)*(4lanes) + (32)*(2mls)*(5lns) + (32)*(1ml)*(2lns) = **1280 veh/mile**]

PM Capacity:

[Capacity = (32veh/lane-mile)*(1mile)*(3lanes) + (32)*(1.5mls)*(5lns) + (32)*(7.5mls)*(4lns) = **1296 veh/mile**]

For the current time interval, the volume present in the zone at that time is then found by summing the average detector occupancy values from the mainline detector station downstream of each ramp throughout the corridor. In this corridor, these are the (D#) detector stations. This current volume is then subtracted from the capacity value to obtain (S). This calculation is completed as shown below:

[Current Volume = Sum(D1 to Dn) * (1.1)] → [S = Capacity – Volume]

Step 3: Using the measured values from the corridor detector stations and the calculated value of (S), the algorithm then calculates the value of the term (X+B+S−A−U) for the current interval.

Step 4: The algorithm calculates metering rates based on threshold values, using a 6-level rate structure, similar to other algorithms. This is a three-part process:

Step 4a: Prior to algorithm implementation, the predefined value of (Mt) is used to calculate thresholds for each metering rate. This is accomplished using the total ZONE value of (Mt), not the individual ramp values.

Step 4b: Second, the value of the term (X+B+S−A−U) is compared to these threshold values, and the rate level for the zone is then chosen.

Step 4c: Third, based on the rate level assigned by the value of (X+B+S−A−U), the individual ramp values of (Mt) are used to calculate the red-time at each ramp meter. The following table depicts these values and their ranges:

Metering Rate	**Threshold**	**Red-Time** (minus Green-time of 2sec)
1	If (X+B+S−A−U) > (1.4*Mt)	(300sec / (1.5*Mt)) – 2sec
2	(1.4*Mt) > (X+B+S−A−U) > (1.2*Mt)	(300sec / (1.3*Mt)) – 2sec
3	(1.2*Mt) > (X+B+S−A−U) > (1.0*Mt)	(300sec / (1.1*Mt)) – 2sec
4	(1.0*Mt) > (X+B+S−A−U) > (.8*Mt)	(300sec / (.9*Mt)) – 2sec
5	(.8*Mt) > (X+B+S−A−U) > (.6*Mt)	(300sec / (.7*Mt)) – 2sec
6	(.6*Mt) > (X+B+S−A−U)	(300sec / (.5*Mt)) – 2sec

Occupancy Rate Calculation

The secondary method of calculation used by the Zone algorithm is a form of localized traffic-responsive control, where detection stations downstream of individual ramps are monitored and metering rates are calculated based on the occupancy at these stations. For the study corridor, detection stations (mainline) are generally considered from the ramp in question through to the 2nd ramp downstream from this site (exceptions occur at each end of the corridor where the distance between some ramps is much greater). The detection stations assigned to each ramp's area of influence are defined in the table below:

SOUTHBOUND (AM) DETECTION AREAS OF INFLUENCE

Ramp Site	Glover Ln	Parrish Ln	400 North	500 South	2600 South
Detectors	D1, D2	D2, D3, D4	D3, D4, D5	D4, D5	D5, D6

NORTHBOUND (PM) DETECTION AREAS OF INFLUENCE

Ramp Site	Beck St	2600 South	500 South	Hwy 89	Parrish Ln
Detectors	D9, D10	D11, D12, D13	D12, D13	D13, D14	D14

Step 5: Occupancy levels used to assign metering rates are listed in the table below. The metering rates shown are the same as those outlined in the full Zone algorithm discussed above. For the secondary rate calculation, the algorithm simply compares the occupancy at the detector stations listed in the tables above, and if these values exceed the flat-rate shown below, then the associated metering rate shown below is assigned to that ramp (N/A indicates that these metering rates are not used in this calculation).

Metering Rate	*1*	*2*	*3*	*4*	*5*	*6*
Occupancy (%)	N/A	N/A	17%	18%	23%	40%

Step 6: Based on the results of both the Zone and area of influence calculations, the algorithm then selects the most restrictive rate calculated for each ramp and implements this as the metering rate for the next interval at each site.

Based on UDOT policy, this is amended for this study corridor, however, and a minimum red-time value of 2 seconds and a maximum red-time value of (13)seconds—neither including green time—are imposed on the metering rates. Any calculated rate which exceeds these max/min boundaries should default to the appropriate max/min value.

There is no discussion in the literature regarding either a smoothing algorithm or a queue override calculation being present in the Zone package.

APPENDIX C – SEATTLE BOTTLENECK ALGORITHM APPLIED TO THE STUDY SITE

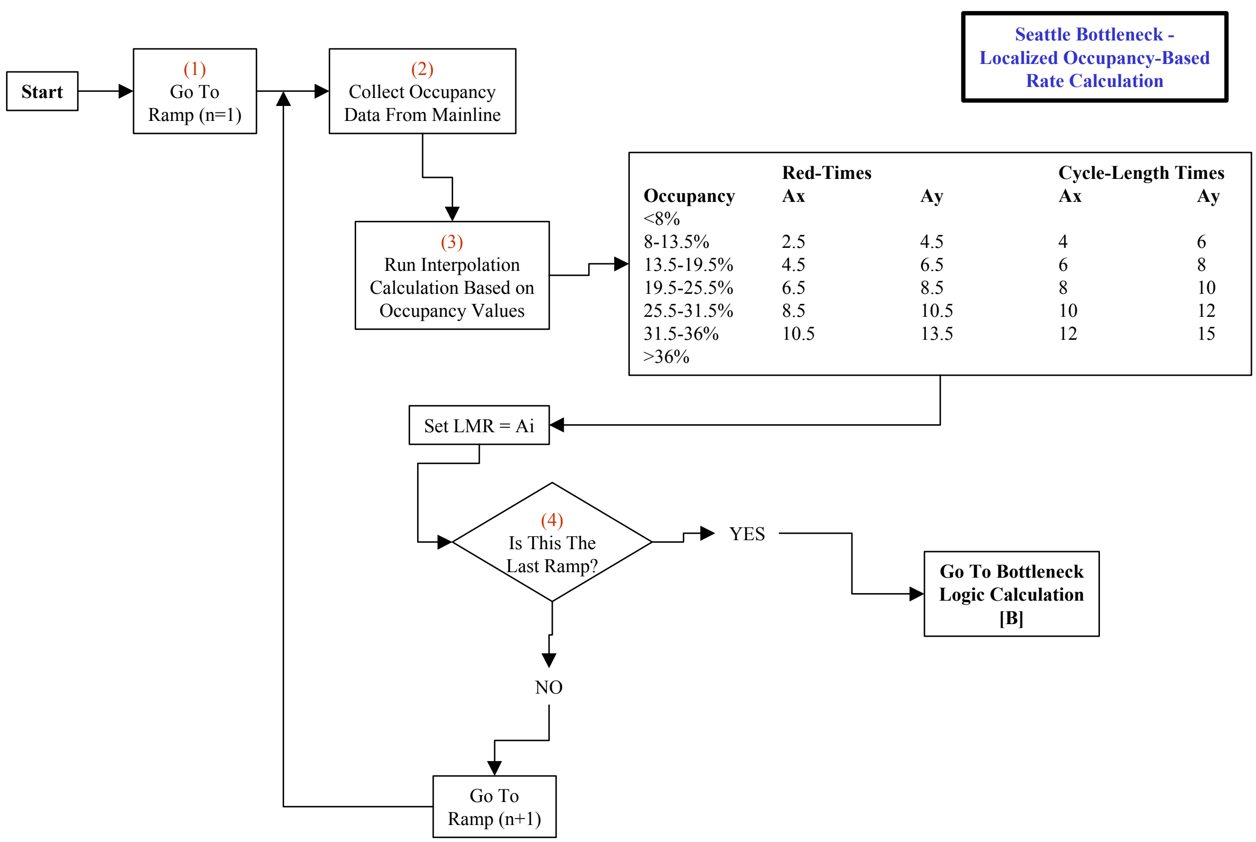
The Seattle algorithm calculates a rate for each ramp using three independent processes:

1. First, a local-responsive metering rate is calculated for each ramp by comparing the measured occupancy from a mainline station just upstream of the ramp with a predefined occupancy/rate relationship curve.
2. Second, the rate at each ramp is calculated based on the mainline flow through a bottleneck point somewhere within the system.
3. Third, calculated rates are either adjusted or overridden based on ramp-specific variables, such as metering violations during the previous period, queue overruns, etc.

This algorithm operates on a 20-second calculation cycle (i.e., the algorithm is run and both calculates and implements a metering rate for all system ramps once every 20 seconds).

Local-Responsive Occupancy-Based Calculation

(The figure & text complement one another— refer between the two accordingly.)



Step 1: For algorithm application, the ramps being metered are identified in numeric order, in the direction of travel. This is not required, but this convention will be followed through the description of the algorithm to assist in its description. The ramps being considered in this study are the following:

AM (Southbound):

1) 2600 South	2) 500 South	3) 400 North	4) Parrish Lane	5) Glover Lane

PM (Northbound)

6) Parrish Lane	7) Hwy 89	8) 500 South	9) 2600 South	10) Beck Street

Step 2: To begin the calculations, data must be collected from the corridor at each detector station of interest. The maps and tables below identify, for the Bottleneck Algorithm, the detector sites where data are to be collected within the study corridor, the name/purpose for their collection, and which of the ramps from Step 1 it should be associated with.

(M) indicates the upstream mainline detector station nearest each ramp entrance.

(Adv) indicates the advance queue detector station—if available—at the head of each ramp.

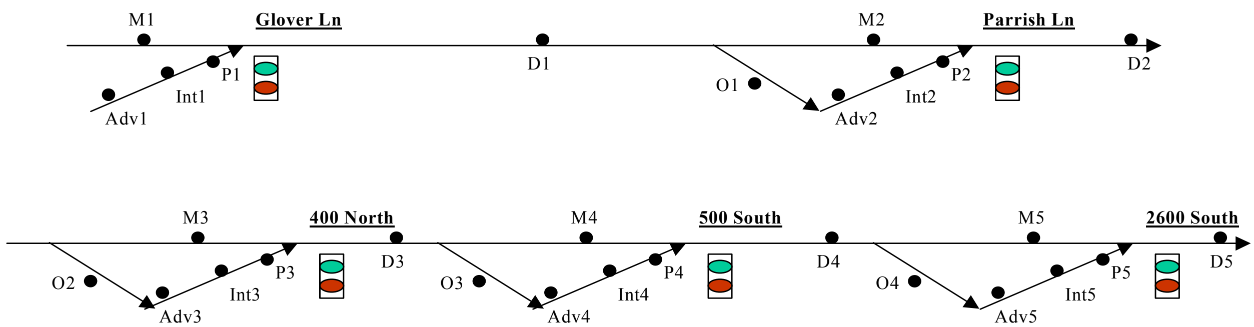
(Int) indicates the intermediate queue detector station—if available—in the middle of each ramp.

(D) indicates a downstream detector between the interchanges shown.

(P) indicates the passage detector loops located just past the stopbar on each entrance ramp.

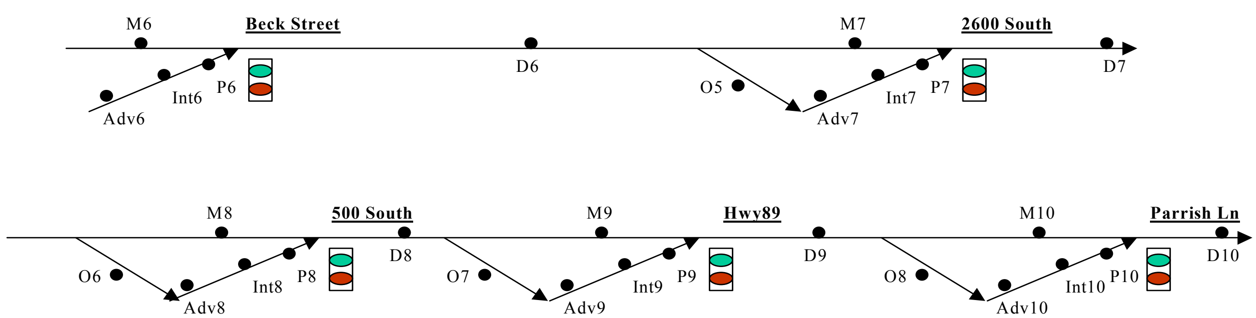
(O) indicates the passage detector loops located on the offramp for each interchange.

Seattle Bottleneck Algorithm - AM Detector Stations



Map ID	M1	Adv1	Int1	D1	P1	O1	M2	Adv2	Int2	D2	P2	O2	M3	Adv3
CORSIM ID														
Map ID	Int3	D3	O3	M4	Adv4	Int4	D4	P4	O4	M5	Adv5	Int5	D5	P5
CORSIM ID														

Seattle Bottleneck Algorithm - PM Detector Stations



Map ID	M6	Adv6	Int6	D6	P6	O5	M7	Adv7	Int7	D7	P7	O6	M8	Adv 8	Int8
CORSIM ID															
Map ID	D8	P8	O7	M9	Adv 9	Int9	D9	P9	O8	M10	Adv 10	Int10	D10	P10	
CORSIM ID															

Step 3: The local responsive rate is calculated using occupancy values taken from the mainline detector station just upstream of the ramp merge area at each interchange—the (M#) detector. The values from all lanes are averaged to produce a single occupancy percentage for the station, and this value is taken as (P_i) to solve the following equation. Solution of the equation produces a value for (A_i) for the ramp, which is then assigned as the Local Metering Rate (LMR).

$$\mathbf{A_i = A_x + [(A_y - A_x) / (P_y - P_x)] * (P_i - P_x)}$$

Where

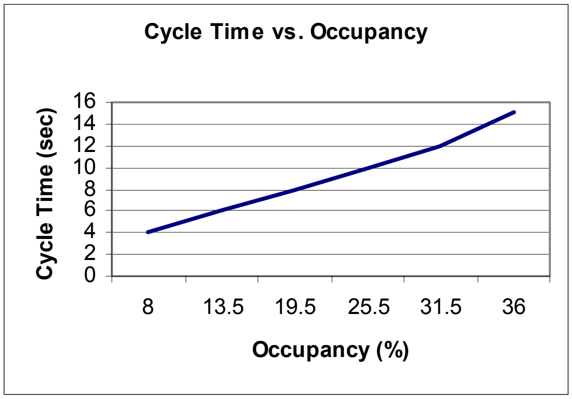
A_i = Calculated metering rate
P_i = Current Occupancy value
P_x, P_y = Known values of occupancy, where ($P_x < P_i < P_y$)
A_x, A_y = Known values of time corresponding to (P_x,P_y), where ($A_x < A_i < A_y$).

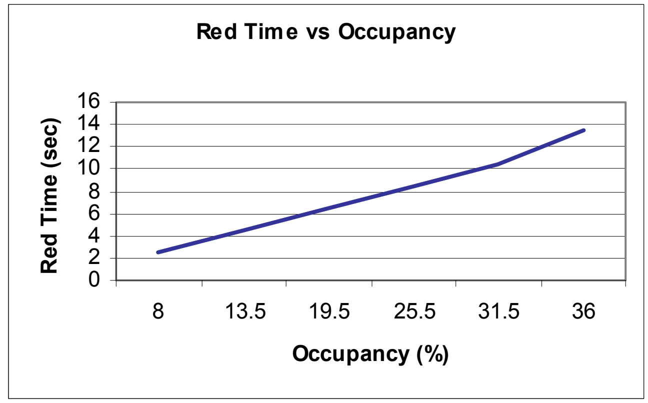
This formula is an interpolation equation, solving for an exact value along a curve defined by the following points (shown graphically below the table):

	Red-Times			**Cycle-Length Times**	
Occupancy	**A_x**	**A_y**		**A_x**	**A_y**
<8%					
8 – 13.5%	2.5	4.5		4	6
13.5 – 19.5%	4.5	6.5		6	8
19.5 – 25.5%	6.5	8.5		8	10
25.5 – 31.5%	8.5	10.5		10	12
31.5 – 36%	10.5	13.5		12	15
>36%					

*** Where (P_i<8%), use Rate 1 values, the minimum allowable by UDOT policy.*

*** Where (P_i>36%), use Rate 6 values, the maximum allowable by UDOT policy.*





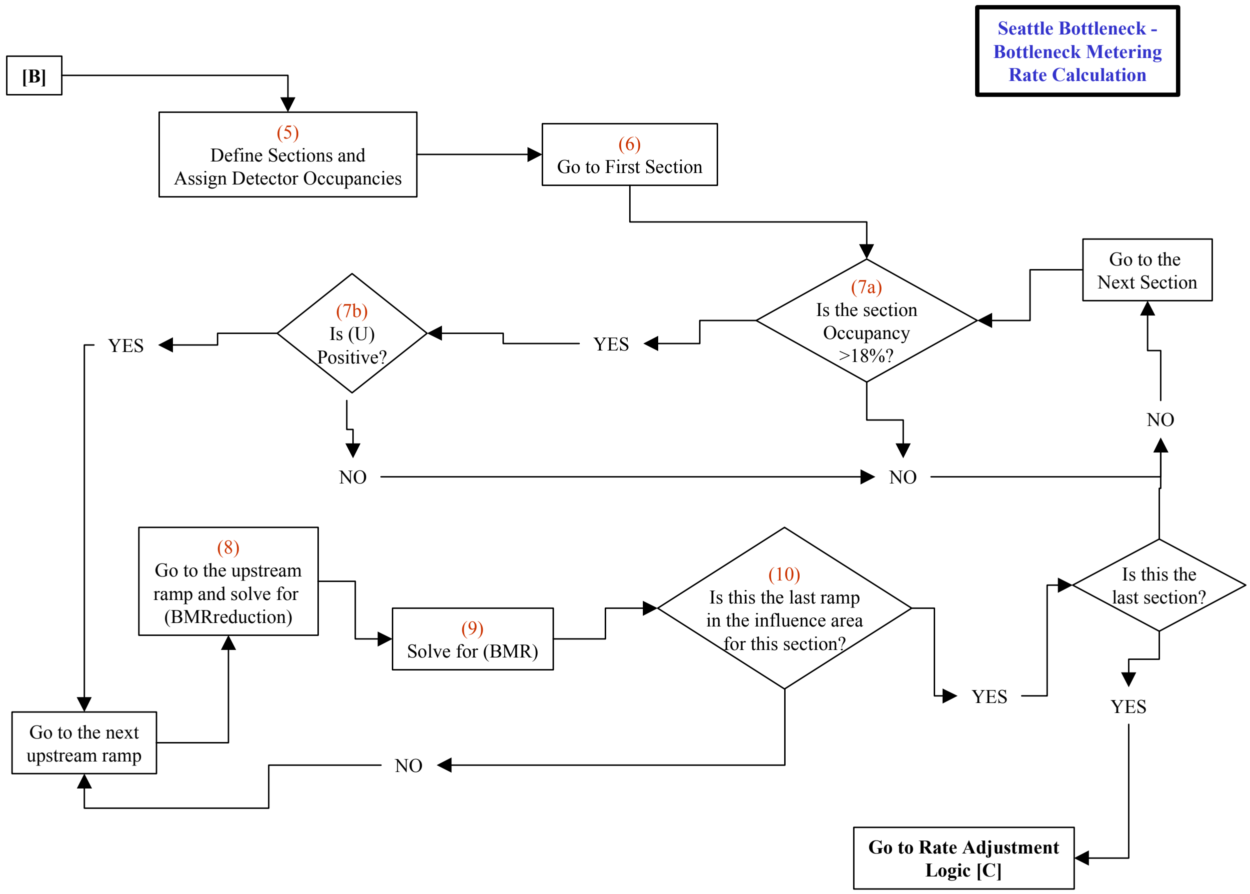
The table and graphs above are based on values taken from *The Traffic Control Systems Handbook (Feb 96, p.4 – 23)*. Adjusting the values shown in the handbook to conform to the general rate limits of a minimum 4-second cycle and maximum 15-second cycle used by UDOT, the base metering rates are defined. The values shown for "Cycle Time" assume a fixed green-time of 1.5 seconds and no yellow lamp.

Rate ID	Occupancy (%)	Metering Rate (vpm)	Red-Time (seconds)	Cycle Time (seconds)
Rate 1	8	15	2.5	4
Rate 2	13.5	10	4.5	6
Rate 3	19.5	7.5	6.5	8
Rate 4	25.5	6	8.5	10
Rate 5	31.5	5	10.5	12
Rate 6	36	4	13.5	15

Step 4: The local responsive rate calculation is iterated for all ramps in the system, to give a value of (A_i = LMR) for all ramps (1) to (n).

Systemwide (Bottleneck) Rate Calculation

(The figure and text complement one another—refer between the two accordingly.)



Step 5: For operation of the Bottleneck algorithm, the ramps within the system are broken into distinct sections. For this corridor, the sections have been chosen as portions of the mainline between two adjacent interchanges. Once defined, specific detector inputs from the model are assigned to each section for calculation of the Bottleneck values. For the AM and PM periods in the Davis County corridor, these sections and detection assignments are defined as follows:

AM (Southbound) Corridor:

Section ID	Upstream Interchange-Mainline Loops	Upstream Detector	Downstream Detector	Mid-Section Detector
Section 1	South of 2600 South	M5	D5	N/A
Section 2	500 South to 2600 South	M4	M5	D4
Section 3	400 North to 500 South	M3	M4	D3
Section 4	Parrish Lane to 400 North	M2	M3	D2
Section 5	Glover Lane to Parrish Lane	M1	M2	D1

PM (Northbound) Corridor:

Section ID	Upstream Interchange-Mainline Loops	Upstream Detector	Downstream Detector	Mid-Section Detector
Section 6	North of Parrish Lane	M10	D10	N/A
Section 7	Hwy 89 to Parrish Lane	M9	M10	D9
Section 8	500 South to Hwy 89	M8	M9	D8
Section 9	2600 South to 500 South	M7	M8	D7
Section 10	Beck Street to 2600 South	M6	M7	D6

Step 6: The Bottleneck algorithm is calculated iteratively for each section in the system, just as for a series of ramps, moving from the first (downstream) to the last.

Step 7: For each section, the algorithm determines whether or not the following two parameters are satisfied, using the value of occupancy measured at the (D#) detector station. If they *are* satisfied, the Bottleneck algorithm runs and calculates a Bottleneck Metering Rate (BMR) for all upstream influence ramps defined for this section. If they are *not*, the systemwide algorithm does not run, and (BMR) is set to a null value. The two parameters are as follows:

Step 7a: The measured occupancy for the section at (D#) must be greater than (18%).

Step 7b: The section must be storing vehicles. This is calculated as a simple summation of input/output volumes for the section, measured at the upstream and downstream ends of each section (detector stations as defined in the tables above) over the past 60 seconds, as:

$$[\ \mathbf{U = (Qin + Qon) - (Qout + Qoff)}\ ]$$

Where

U = volume of storage during the last 60 seconds

Qin = mainline upstream volume entering the section (M1 for AM, M6 for PM)

Qon = onramp volume entering the section (Sum of P1 to P4 for AM, Sum of P6 to P9 for PM)

Qout = mainline downstream volume leaving the section (M5 for AM, M10 for PM)

Qoff = offramp volume leaving the section (Sum of O1 to O4 for AM, Sum of O5 to O8 for PM)

If the value of (U) is positive, the section is storing vehicles and the parameter is satisfied. If (U) is zero or negative, the section is operating at equilibrium or is discharging vehicles, respectively, and the parameter is not satisfied.

Step 8: If Step 7 is satisfied, the positive value of (U) then represents the volume of vehicles stored in the section during the past minute. To address this excess storage, the algorithm applies a set of predefined weighting factors to calculate inflow reductions for the next interval at each ramp upstream of the given section, within a defined area of influence. The sum of these upstream ramp inflow reductions must equal (U).

For each ramp upstream of the section and within the area of influence, the following equation is solved to obtain a metering rate reduction volume for the next time interval ($BMR_{reduction}$):

$$[\ \mathbf{BMR_{reduction} = U * (WF_n / (sum\ of\ WF_1\ to\ WF_n))}\ ]$$

Where

$\mathbf{BMR_{reduction}}$ = Reduction in ramp inflow (vpm) required at the given ramp

$\mathbf{WF_n}$ = Weighting factor for ramp (n)

For the South Davis corridor, the following weighting factors have been assigned to each ramp for the sections indicated. Those cells which are shaded indicate ramps either within or downstream of the calculated section.

AM (Southbound)

Section Calculated	2600 South WF	500 South WF	400 North WF	Parrish Lane WF	Glover Ln WF
Section 1		1	2	2	N/A *
Section 2			2	2	N/A *
Section 3				2	1
Section 4					1
Section 5					

** Due to the 3-mile distance between the Glover Ln. and Parrish Ln. interchanges, the Glover Ln. ramp is only considered as part of the area of influence for Sections 2 and 3.*

PM (Nortbound)

Section Calculated	Glover Lane WF	Parrish Lane WF	Hwy89 WF	500 South WV	2600 South WF	Beck Street WF
Section 6			1	2	2	N/A **
Section 7				1	2	N/A**
Section 8					2	1
Section 9						1
Section 10						

** Due to the 2.5-mile distance between the Beck Street and 2600 South interchanges, the Beck Street ramp is only considered as part of the area of influence for Sections 7 and 8.*

Step 9: Once (BMR_reduction) is calculated for ramps upstream of the section, the algorithm then reduces the previous interval's metering rate (BMR_p) by the value of ($BMR_{reduction}$) to calculate the metering rate (BMR) for the next interval. This is calculated as

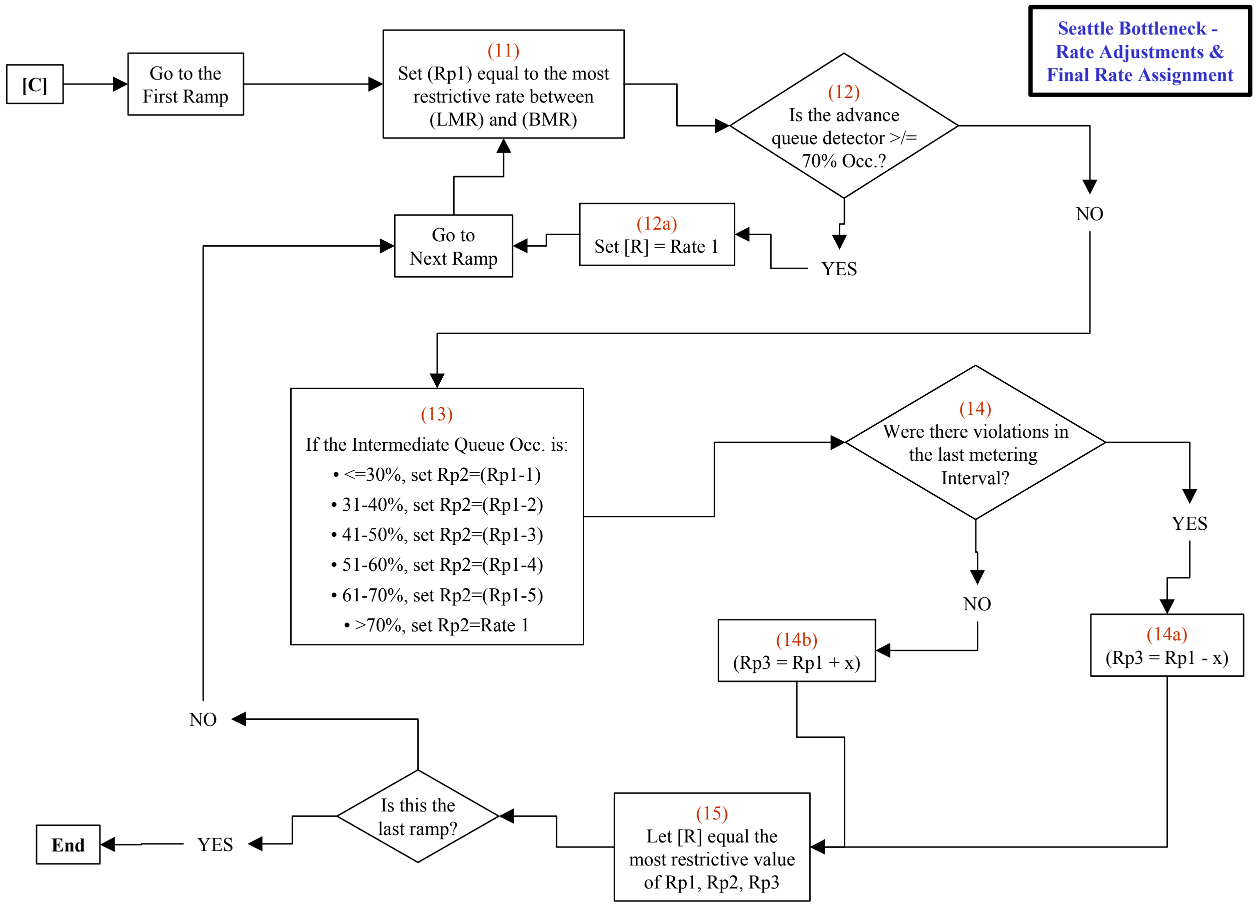
$$[\ \mathbf{BMR = BMR_p - BMR_{reduction}}\ ]$$

Step 10: The above process is iterated for all sections and influence ramps for each section. This results in the possibility of numerous values of (BMR) for each ramp, where each value of (BMR) is based on a different value of (U) for different downstream sections. The most restrictive of these multiple (BMR) values for each ramp is then taken as the final (BMR) value for that ramp, and is carried over to the third phase of the algorithm calculations.

Once all sections and influence ramps have been accounted for, the algorithm moves on to calculate any required rate adjustments.

Rate Adjustments Calculation

(The figure and text complement one another—refer between the two accordingly.)



In addition to the (LMR) and (BMR) metering rates calculated for each ramp, the algorithm incorporates several rate adjustments to account for ramp queuing and meter violations. The algorithm iterates the following logic for each ramp in the system.

Step 11: Once the values of (LMR) and (BMR) are known, the most restrictive rate calculated at each ramp is taken as the preliminary metering rate for that site during the next metering interval, and becomes the base rate for applying rate adjustments. For the purpose of applying these adjustments, this preliminary rate will be labeled as (R_{p1}).

Step 12: The first adjustment examines the advance ramp queue detector. If the occupancy at this detector station exceeds 70%, then the final metering rate [R] is set to Rate 1 to clear the ramp and prevent surface street backing off the ramp (Step 12a). This overrides all other rate calculations for this ramp for the next interval, and if satisfied, the algorithm is complete for this onramp and moves on to the next ramp. If the occupancy value is less than 70%, no action is taken.

Step 13: The second adjustment examines the intermediate ramp queue detector. If the occupancy at this detector station falls into one of the value ranges shown below, then (R_{p1}) is reduced by the number of Rate levels indicated.

- 21 – 30%, set R_{p2}=(R_{p1}-1 Rate)
- 31 – 40%, set R_{p2}=(R_{p1}-2 Rates)
- 41 – 50%, set R_{p2}=(R_{p1}-3 Rates)
- 51 – I60%, set R_{p2}=(R_{p1}-4 Rates)
- 61 – 70%, set R_{p2}=(R_{p1}-5 Rates)
- >70%, set R_{p2}= Rate 1

** There is no basis in Bottleneck algorithm literature for the intermediate queue detector adjustments given here; the algorithm is known to simply reduce (R_{p1}) by some number of vehicles. As such, a metering-rate increase model based on that used by the Denver Helper algorithm has been assumed here, because this fits both the high-level theory and real-world methodology defined in the literature, while still providing realistic values.

Step 14: At each interval, the algorithm collects a count from the ramp passage detector (see detectors P# on maps above) at each location to determine the number of vehicles that entered the mainline from this point during the previous 20 seconds. The algorithm then compares the volume taken from (P#) to the number of vehicles which should have entered, based on the metering rate assigned for the previous interval, and either increases or decreases the value of (R_{p1}) accordingly to calculate a value for (R_{p3}):

Step 14a: If there were (x) number of violations, then [$R_{p3} = R_{p1} - x$].

Step 14b: If (x) fewer vehicles entered than what were allowed, then [$R_{p3} = R_{p1} + x$].

Step 15: The final rate assignment for each ramp is determined by taking the most restrictive value from among (R_{p1}, R_{p2}, and R_{p3}) and assigning this value as [R].

For the purposes of the South Davis application of this metering algorithm, the maximum cycle allowable shall be 15 seconds (total cycle length), and the minimum cycle allowable shall be 4 seconds (total cycle length). Any calculated cycle length or red-time which results in a metering rate beyond these max/min boundaries should be automatically defaulted to these values by the algorithm.

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APPENDIX D – DATA PREPARATION

Data preparation is one of the most time-consuming tasks of any simulation study, especially for a simulated highway section as large as this one, both in terms of size and simulation period (a 10-mile freeway with several crossing streets and a 3-hour simulation period for both am and pm peak periods). Also, the lack of a unified data set for the simulation work caused the model building task to take longer than initially planned. Additionally, the data requirements were dependent on the simulation software used for the analysis. Thus, to meet the goals of the study, simplicity had to be balanced with accuracy.

A traffic simulation software package, WATSim© (KLD 1999), created by KLD Associates, was used for the study. WATSim© was developed as an integrated simulator of the surface streets and the freeway as one network and overcomes the one weakness of the corsim software by FHWA (FHWA TSIS undated)—the connection of NETSIM for street networks and FRESIM for freeway networks within CORSIM is made by the ramps. Hence, integrated analysis of ramp operation and surface street analysis is somewhat awkward. WATSim© model files and CORSIM model files are similar in many ways. When the study was started, KLD's graphic data input preparation software, unites, was not available; hence, two software packages, ITRAF (FHWA ITRAF undated) and TRAFVU (an animation program of TSIS software), were used to codify and verify a simulation model of the study area for WATSim©.

WATSim© creates a virtual network of links (roads) and nodes (intersections) based on the information in the input data file, runs the simulation, and generates an output file based on the information that is provided in a text document, referred to as a data input file. An understanding of the structure of the data input file and how the simulation software uses that information is necessary to facilitate the collection and organization of the input data. Each line of the input file, or record, contains 80 columns of data. These records are designated by a number, which is placed in the last three columns of the line. The record number identifies what information is contained in that particular line of the file and how WATSim© will use that information in the simulation. The record types for this study can be categorized into three groups of data (program data, geometric data, and traffic data), based on their relation to the simulation model. Program data consist of the governing parameters for the simulation, such as time increments for simulation and data collection, as well as the format of the output. The geometric data contain all the roadway information, including the layout of the street network using the aforementioned links and nodes. The geometric records also include other information, such as the number of lanes and speed, both used in the simulation, and graphical options that allow for a more realistic graphical representation of the simulation network. The traffic data consist of the traffic control, including the sensor locations and timing of the signals, as well as the traffic volumes and turning movements of the network.

The data that describe the network being studied have been gathered from many sources, including other researchers, UDOT, and construction plans (see the data sources section of References). Most of the data used reflect the conditions in 1998, such as volume counts and signal timings, but some data come from different years. Differences existed among some overlapping data from multiple sources, and some necessary traffic and geometric data could not be found. Several site visits were made in order to fill the holes in the existing data that had been gathered. Basic data needed to run the WATSim© simulation include program data, geometric data, traffic data, and control data. These are briefly discussed in the subsections below. For detailed discussions of record types, see the WATSim© User Manual (KLD 1999).

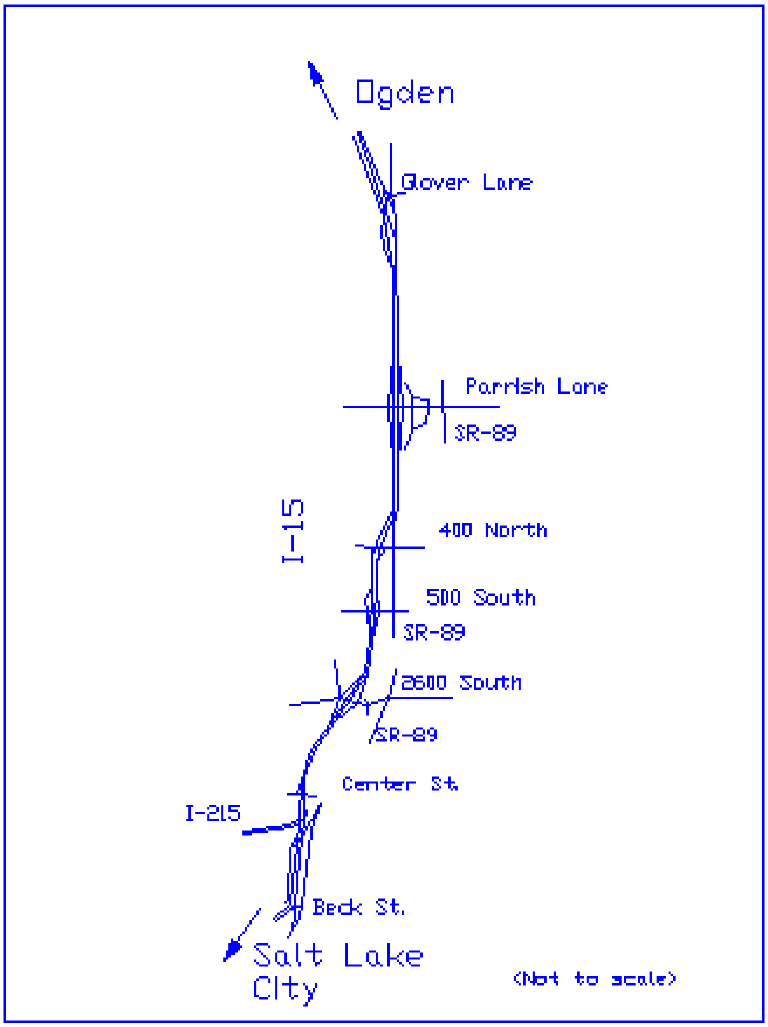


Figure D.1 Model of the study site.

D.1 Program Data (Record Types 00, 01, 02, 03, 04, 05, 170, 210)

The program data relate to how WATSim© reads the input file, performs the simulations, and reports the results. The simulations for this study will model the morning and evening peak three-hour intervals, from 6:00 AM to 9:00 AM and from 3:00 PM to 6:00 PM. These three-hour blocks are further broken down into 15-minute segments, allowing for a more accurate representation of the actual traffic conditions. By looking at the results of the simulations for each 15-minute block, the traffic characteristics, such as queuing, are more noticeable and realistic. As well as being studied individually, the different areas can also be compared against each other under the different types of control analyzed in this study. The categories of what information is contained in the output files cannot be changed, but the time periods for recording the data can. In this case, results for each 15-minute time period, as well as hourly summaries, were designed in the program data.

D.2 Geometric Data (Record Types 10, 11, 195, 196)

The network setup involves the use of several different input record types, in order to properly represent and simulate the existing network. Record types 195, 11, 10, and 196 are used to create the geometric features of the simulated network.

Record type 195 contains the (x, y) coordinates of each node, identifying the locations of the different intersections. This information is also used to view the network graphically. Many of the other record types were related to the coordinate data identified in this record type.

The next record type to be coded, record type 11, was then created using the data available. This record is the source of the most of the geometric data for the links in the simulation. First, the “to” and “from” nodes for each link are listed, thus identifying its direction. Then the number of lanes, speed, turning bay configuration and number, lane channelization, and so forth are listed. The lanes and turning bays are also numbered in order to designate the various traffic movements from one link to another.

Once the links were created, record type 10 identified each with a street name. This served the purpose of relating the simulation network to the actual roadways that are being simulated. Identifying a link by name helps to clarify and simplify the identification of the links while inputting the data or viewing the network graphically. At this point, a spreadsheet was also created to help identify and track each link and its attributes.

The final record type in the geometry group, record 196, is used to fine-tune the graphical output of the simulation. This record identifies the curvature of each roadway link, designates overpasses and underpasses, and contains the graphical length. These items allow for a more realistic graphical representation of the network.

<u>Step 1: Initial Network Layout</u>

The first step in coding the data for the simulation was to set up the geometry of the network. The geometry setup includes creating the nodes and links that will be used to model the actual network of the study area. The nodes are assigned (x, y) coordinates, designating their location on a grid. The nodes are also assigned numerical names to aid in their identification and use in the simulation. Specifying the names of an upstream node and a downstream node designates each link. Using these two points, the simulation program creates a link with traffic flowing in the designated direction, from upstream to downstream. Each link can support traffic flow in only one direction. Therefore, in order to simulate two-directional traffic, a link for each direction is necessary. The grid on which the network was created was set up with the entire network in the positive quadrant (meaning that all x and y coordinate values are positive numbers). This was done because some of the software used for the creation of the simulation data would not recognize negative coordinates.

In order to identify the placement of the nodes on the network grid, accurate geometric data, based on the actual network, are essential. Many different sources of geometric data were explored for use in this study. These data sources included maps, electronic data (CAD, GIS, etc.), construction plans, field observations, etc. All of these data types were used in the identification of the study area streets and intersections, providing the most accurate data set possible. When creating the initial rough network, maps were the most useful source of geometric information, allowing for the preliminary network to be created quickly. An effort was made to locate electronic versions of the study network already in existence. However, after checking with various government agencies, as well as speaking with other researchers, a suitable data set of the entire network could not be found, so the existing map data were used for the initial network setup.

Initially, a map was used to create an (x, y) grid on paper to aid in the placement of the nodes by identifying their coordinates. Based on the map and its scale, the rough node locations were identified and coded into the data file. These records are created relatively quickly, since the only data they contain are the node numbers and their (x, y) coordinates. Initially the network grid was set up based on a paper map and its coordinate system. Once a rough network was set up, the text file that contained the information was prepared. However, as construction of the network proceeded, the size and manageability of the large number of nodes required for the network became an issue. In order to better organize and manipulate the data file, the nodes were assigned certain numbers, based on their location and function. The following are the groups of numbers used to identify each node and a description of what type of node is contained in each group:

100 – freeway nodes (NB started with 100, SB started with 150)
200 – ramp nodes
300 – ramp meters
400 – freeway nodes
500 – WATSim© network
600 – WATSim© network
8000 – sink/source nodes

Once the basic network had been created, two different programs were used to view the data graphically, aiding the refining of the simulation network. These programs are ITRAF (FHWA ITRAF undated) and TRAFVU (FHWA TSIS undated). ITRAF is a program designed to facilitate the creation of these types of networks by providing menus and graphics to allow the creator to visualize the network and add a large amount of data relatively quickly by providing drop-down menus and data entry fields that place the input data into the correct text format to be read by the simulation software. However, this program has some limitations when dealing with more complex networks and was therefore only used to view and create plots of the link-node network. From ITRAF the network could be plotted at 400% of the size seen on the screen, greatly facilitating the creation of the network.

The other program, TRAFVU, is the simulation component of CORSIM and was used to view the network and to find and fix errors in the syntax of the data. When opening a data file using TRAFVU, the program reads the data and identifies any errors in an error file. This file is then used to make corrections to the data file. When the initial data file was input into TRAFVU, some minor changes had to be made in order to use these programs to view the data. These changes included making all coordinate values positive, putting the data types in order, and lining up some of the nodes and links. These problems were quickly fixed, allowing the network to be viewed graphically. However, based on the size of the network and the inability to view such a large network on a computer screen, it was determined that having a hard copy of the network would be beneficial in the further editing of the data file. A large link-node map of the entire network was created using screen captures of each area of the network and piecing them together. A large plotter was later used to avoid having to paste together many sheets of paper.

Step 2: Refinement

After the necessary nodes were in place, the first step was to look at the record type 11 more carefully, checking alignment, channelization, and what nodes were assigned the traffic from each link. One necessary change was the addition of nodes to limit the lengths of the links to less than 4000 ft, the limit allowed with WATSim©.

With the basic network being operational, the model was refined in order to the modeled network as close to reality as possible. A balance between simplicity and accuracy was necessary due to the large scale of the network and the limits of the software. Interchanges were reviewed most closely, as they were the focus of the study. The freeway portion of the network was looked at first. As-built UDOT roadway plans, information taken from Taylor's work (Taylor 2000), and site visits were the major resources used to create the geometric network of the study site. The network was reviewed to determine if any nodes should be added or deleted. Data from site visits were used to confirm the geometric layout already created for the study network, as well as to determine if some of the intersections could be removed without affecting the simulations. In particular, site visits reviewed the number and length of traffic lanes, the slope, and the existence and length of turning bays. An example of an area looked at closely was the area of the interchange at 2600 S. On the west side of the freeway, the distance between the intersection of the ramps and the intersection with 800 W. is very short; thus it was necessary to model this section as much as realistically possible.

After the network had been laid out, overpasses and underpasses were designated. Channelization of traffic at the various intersections was also verified and coded. Channelization is useful for two reasons: (1) to accurately portray the traffic movements, and (2) to provide a visual verification of the traffic movements—the graphical display shows the channelization arrows.

As the freeway network was reviewed relative to lane configurations, locations of auxiliary lanes, and existing ramp meters, it was determined that the construction plans being used lacked existing ramp meter or sensor locations. Additional as-built plans for the existing meters and a striping plan for the expanded freeway were made available by UDOT. Further refinement of the network was accomplished with the use of these roadway and striping plans for the reconstructed freeway. This helped to improve the accuracy of the model by removing redundant freeway mainline nodes and creating auxiliary lanes. The striping plans were the most useful, since they designate the actual travel lanes. On the other hand, the roadway plans were useful for the identification of the physical features of the roadways and the locations of the detectors and ramp meters.

Unnecessary nodes (not needed for intersections, traffic control, or alignment changes) were removed from the ramps. Additional nodes were located in places where a lane is dropped. In WATSim©, lanes can be added in the middle of a link with relative ease (for instance, adding a turn lane). However, in order to drop a lane, a node must be placed at the location where the lane is to be dropped, and a receiving link with fewer lanes is placed from that point. It was determined that this setup was especially necessary where a ramp comes into the freeway. By adding the short link with a lane drop, we were able to see how the cars behave as they attempt to merge into traffic.

Another problem encountered was that ITRAF supports link lengths greater than 9999 ft. However, when the information is placed in Record 11, the first numeral replaces the last number of the downstream node for the link. Therefore all links must be less than 9999 ft., but ITRAF does not warn the user of this problem if it occurs. Our assessment of ITRAF is that it is useful, but the user needs to be extremely cautious about its capabilities.

The network was analyzed to determine if any needed detectors would be on an entrance link. If that was the case, an additional node was added between the entrance node and the intersection, creating a link that could sustain a detector adjacent to the intersection.

On the ramps where a true acceleration/deceleration lane did not exist, a short lane was added to simulate the existing physical layout. The area of 400 N., where the NB off-ramp is channelized for either left or right turns with an island in the middle, was coded simply as a t intersection. The limitations of the software and graphics would not allow for an accurate portrayal of the turning roadways.

An area of interest was at the ramps at 500 S., which were being reconfigured with the freeway widening. This area originally had a cloverleaf ramp for the NB off-ramp. This ramp was removed during the recent reconstruction, and all vehicles exiting NB will now use the same ramp. This new ramp was aligned with the NB on-ramp, creating a 4-way intersection.

Many of the netowrk ramps and connecting freeway segments were longer than they should have been. Small differences of less than 50 ft were ignored, but many segments were off by as much as 500 ft requiring adjustments in the model. All locations of the ramp meters were found except for the meter at 2600 S. to NB I-15. We used our own judgment to add a ramp meter to this on-ramp.

An inconsistency between the data file and the actual configuration of the channelization of traffic at the intersection of Parrish Lane and Marketplace Dr. was noted during a site visit. The proper lane configuration was noted during the visit and addressed in the data file.

Step 3: Verification

First the freeway alignments were checked and finalized, after which the remainder of the surface streets and their intersections were checked. The first source of information about the surface streets was data from Taylor's Synchro files (Taylor 2000). However, a number of changes needed to be made. It was decided that the intersections at 400 N. and 500 S. and the freeway ramps could be simplified without the short road segments. Another intersection that needed further study was Lagoon Dr. and State St. in Farmington. Using images from www.terraserver.microsoft.com, it was determined that the two roads do not intersect. Rather, State St. passes over Lagoon, and they are connected by a short piece of 400 W. This was confirmed with site visits. Based on this new knowledge, as well as a lack of data for this intersection and the fact that the intersection is at least 1 km from the ramp area, this intersection was removed from the simulation.

Another One area of interest in the site visits is that of 2600 S. in Bountiful. The maps are unclear as to how the many roads actually intersect and what traffic movements are allowed. Site visits determined that the intersection of 2600 S. and 400 E. is stop controlled, with the northbound traffic limited to right turn only. Wildcat Way intersects with 500 E., and the shopping area main entrance is off of Wildcat Way. These changes were made to the network.

In addition to correcting these errors, the network was reviewed to determine if any of the detectors required to collect traffic data were located on entrance links. With WATSim©, entrance links have no real length, and therefore cannot contain any detectors. For any detectors that had been located on an entrance link, an additional node was added between the entrance node and the detector, creating a link that could sustain a detector adjacent to the intersection. Another item addressed at this point was the identification of the locations of the stop bars for the ramp meters. The striping plans were used to determine the locations of the stop bars. The stop bars indicated the point at which the ramp meter nodes would be located and also gave a reference point for the placement of the metering detectors. When reviewing the striping plans, it was discovered that in addition to the standard lanes on the ramps, UDOT was incorporating HOV bypass lanes around the meters. This placement of nodes to include the bypass lanes proved to be somewhat tricky. KLD Associates offered their help in identifying how the links and nodes should be created in order to properly demonstrate the bypass lanes (see Figure D.2).

The final geometric changes were mostly cosmetic. All links were checked for curvature and for the presence of grade separations. Any necessary changes were made to record type 196. These changes were of use only in the graphical representation of the network.

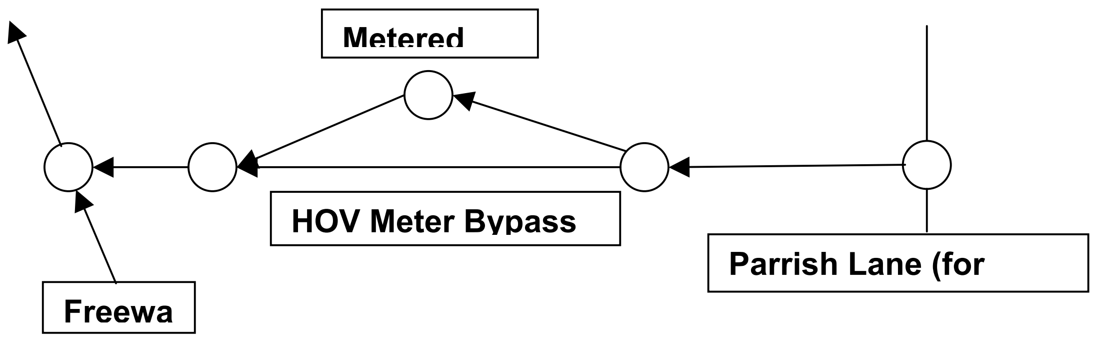


Figure D.2 Layout of HOV bypass lanes.

D.3 Traffic Volume Data (Record Types 21, 50)

The two record types required for the coding of the volumes are record type 21 and record type 50. Record 21 designates the percentage of vehicles making whatever movements are allowed from that link. Record 50 designates the locations where vehicles are introduced into the network and the number of vehicles. Also included in record type 50 is the truck volume percentage.

Bus routes were also explored for their effect on the flow of traffic. Because the number of buses using the network was minor compared to the overall traffic volume, they were assumed to be covered by the truck percentages.

Step 1: Collecting the Volume Data

Several sources for volume data were used, to avoid having to perform extensive traffic counts for the network. The main source of volume data was the existing traffic counts that had been performed by UDOT (see the data source section of References). Most of the network intersections were accounted for in these data. However, little information could be found for the freeway data. UDOT's freeway volume data were therefore augmented with the research by Tabor (Tabermatics 1999). The final source for turning volume data was the site visits that were made several times during the duration of the research.

First, all the existing traffic counts were compiled and sorted to identify which pertained to the study area. Next, the counts were divided into AM and PM data. These were then separated into those counts that contained a full three hours of data and those that covered only a portion of the three-hour blocks. After the initial sorting of the data, some of the intersections for the network were missing data. Full three-hour counts existed for approximately half of the intersections, and about 25% more had partial counts. Therefore, other options were explored to find the necessary data. UDOT reported that their traffic signal group does not perform extensive traffic counts; rather, they rely on the actuated signals and make minor adjustments as needed. Turning movements for the freeway portion of the network were available from previous research by Tabermatics (1999). Also, data from WFRC were reviewed to determine if they could be used to fill in the holes. Once these options were exhausted the remaining counts were made on site. These counts are used for both the internal turning volume percentages (record type 21) and the entrance volume amounts (record type 50).

During each visit, traffic patterns were observed and some volume data were also collected. The first item addressed in the field observations was to record the turning volume movements necessary to finish the model. For the AM period, 7 intersections needed counts. For the PM period, 6 counts were needed. Fifteen-minute intervals were used for each count. However, time constraints resulted in some of the counts lasting less than 15 minutes; these short counts were extrapolated into a 15-minute interval, assuming the rate was the same for the remainder of the counting period. When not using electronic counters, the higher volume intersections were counted one approach at a time.

Included in the setup of the volume data was the breakdown of the 15-minute volumes for the peak AM three-hour period. This information aided in the analysis of the simulation results. When looking for anomalies in the traffic characteristics, knowing when the greater 15-minute volumes occur allows for the analysis to focus on those time periods.

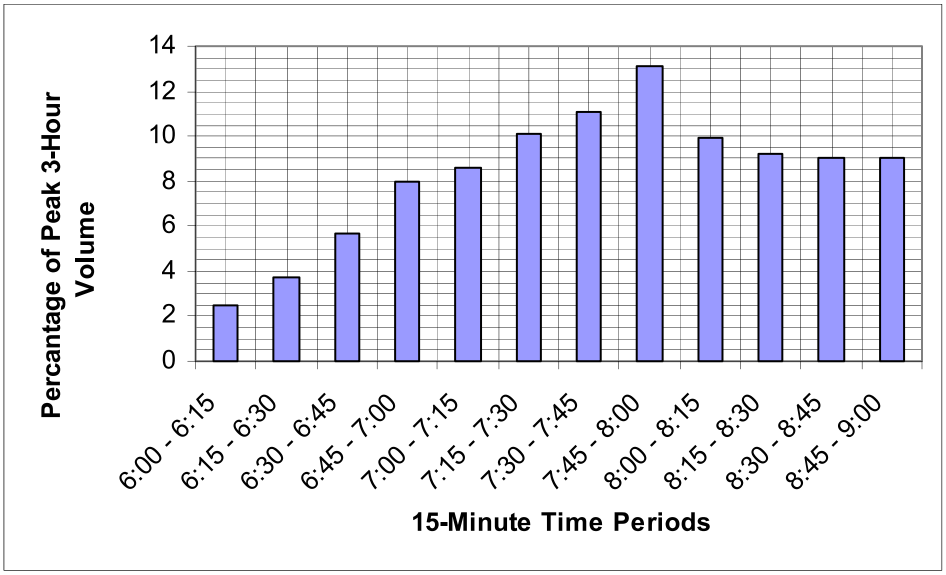


Figure D.3 AM peak three-hour volume distribution.

The chart shown in Figure D.3 was created using the complete three-hour turning volume data that were available for many of the intersections in the study network. These data were taken from the traffic counts for each node and input into a spreadsheet. In this spreadsheet, the volumes for all of the intersections available were averaged and compared to an average three-hour total. This breakdown of the volume data percentages is also used in the coding of the volumes for the data input file addressed in the following sections. This information was used to extrapolate the full three hours worth of data from any count that was lacking this information. However, because this process results in the introduction of potential errors in the data file, it was used sparingly.

Step 2: Coding the Network Entrance Volumes

The first step in creating the traffic data was to identify the truck percentages for each link. The truck percentages from *1998 Truck Percentages on Utah Highways* (UDOT 1998) by the UDOT Data Analysis Section were entered into record type 50. The default percentage was 2%.

The entrance node volumes must be coded as hourly flow rates; therefore, the 15-minute volumes that were used to determine some of these entries had to be converted to the one-hour flow rate by multiplying the 15-minute volumes by four, assuming the peak hour factor of 1.0.

Step 3: Coding the Internal Node Turning Movements

Turning volume movements can be coded as either actual volumes or percentages for each 15-minute block of time.

The process for coding the turning volumes was straightforward. First, many of the nodes have only one link leaving. Therefore, 100% of the traffic flows to that link. This information was consistent for all of the simulation periods, so it did not have to be repeated. The remainder of the turning movement data was then added for each time period for which it was available, with 12 different sections of record type 21 present in the data input file. The difficult part of this process was keeping track of which links had volume data entered, and which were lacking data. For this purpose, a spreadsheet was created to document the volumes entered for each link and used as a checklist to know when the volumes had been entered.

Step 4: Synthesis of Future Volume Data

The first step in the process of creating new files for the various situations that were to be simulated was to create several copies of the original data file and modify all volume data in the file.

D.4 Control Data (Record Types 35, 36, 42, 43, 44, 45, 46, 47)

This set of data can be divided into three groups: sign/pre-timed/no control (record types 35 & 36), actuated control (record types 43, 44, 45, 45, & 47), and freeway control (record type 42).

Step 1: No Control and Sign Control

Based on a sample file that was available with the WATSim© software, all freeway intersections are coded as all green.

The ramp meter nodes also were coded as perpetual green. Consequently, these ramp merge locations allow the WATSim© programs merging traffic function to properly model the merging situation. The Ramp Metering Simulation System (RMSS) takes care of the actual meter control.

Step 2: Actuated Control

According to UDOT, all the signalized intersections in the model network are actuated signals. Setting up these signals proved to be the most difficult task in laying out the control of the network. Some traffic control data were available electronically that aided in setting up the timing of the signals located at some of the intersections. Synchro files used to study the coordination of the signals in the area were available from Taylor (2000). The conversion from Synchro was simple and relatively accurate. Some minor corrections had to be made once the converted signal information was inserted into the data file. Using this existing data sped up the coding of the input data. Unfortunately, not all of the actuated signals for the network were present in the existing data. The intersections that did exist were converted from Synchro, while the remaining intersections were created from scratch. One such case was the ramp intersections at 500 S. in Bountiful. Prior to reconstruction, this interchange made use of a single quadrant cloverleaf configuration. The new configuration for the interchange is that of a compact diamond, with signalized intersections at the ramps. Additional intersections that lacked the existing actuated signal data were those on Parrish Lane. For these intersections, existing data for similar intersections were used as a base, modified in Synchro, and then converted to the CORSIM format, which can be read by WATSim©.

Step 3: Freeway Control

Two different classifications of freeway detectors are used, but both fall under the record type 42. The first is a mainline detector that appears in pairs and collects data on the mainline freeway segments. The detectors are used by the program to collect such data as volume and speed. In order to project the meters across multiple lanes of traffic, WATSim© takes the sensors as a range between two lanes and fills in between the two given values. For example, if lanes 1 and 4 are coded in the data file, WATSim© will assume that the sensors cover lanes 1 through 4. This is unclear in the explanation in the WATSim© manual for record type 42. Also, for a pair of detectors on the freeway mainline, each part of the pair is coded as a separate detector. Another customization of the software links the separate detectors as a pair. The second type of detector is part of the metering systems on each of the ramps. For on-ramps, these detectors record the number and location of the vehicles entering the freeway after passing through the meter, or queued up at the meter waiting to enter the freeway. Detectors are also placed on the off-ramps to record the number and location of the vehicles that exit the freeway. The location of these freeway meters were based on their location in the as-built and construction plans obtained from UDOT.

APPENDIX E – RAMP METER SIMULATION SOFTWARE DEVELOPMENT

KLD Associates, a member of the study team, created software to effectuate several ramp metering algorithms, working together with Brigham Young University and the University of Utah. These algorithms include local responsive metering and the Minnesota Zone, Denver Helper, and Seattle Bottleneck algorithms. This Ramp Meter Simulation System (RMSS) simulates and evaluates the operation of traffic in response to any of these metering algorithms. Specifically, the system executes the WATSim© model; provides sensor data from the simulator to a preselected ramp meter algorithm every 20 to 30 seconds depending on the algorithm; runs the algorithm to compute meter rates for the next processing interval; and returns these rates to the ramp meters in the simulation model.

The results of this process include an extensive set of measures describing traffic operational performance; an animation display of simulated traffic operations identifying vehicle movements, queues, and the changing state of each ramp meter (red, green); and results of all metering computations throughout the run. Thus, the system can be used to evaluate potential benefits of ramp metering under any set of traffic conditions. The RMSS can be useful to UDOT, as well as any agency considering implementing ramp metering, to compare the relative effectiveness of each of these algorithms and determine the most appropriate algorithm for expected traffic conditions.

A schematic representation of the RMSS is shown in Figure E.1, which illustrates the various software components of the system, the connections between software components, and the dynamic data transfer between WATSim© and the ramp metering algorithms while WATSim© is running. As this figure shows all software components, with the exception of WATSim© and its companion AWATG animation software, were newly created under this project.

All new components were coded entirely in JAVA and include:

- Faithful and complete representations of each of the four ramp meter algorithms
- A generic interface between the ramp meter algorithms and the simulator
- A user-friendly Graphical User Interface (GUI)

Each of these software components is briefly described below.

Ramp Meter Algorithms

The RMSS software implements the logic of the Denver, Seattle, and Minnesota algorithms as described in Appendices A through C. A local responsive algorithm is also included based on the local responsive logic of the Denver algorithm. The Denver Helper algorithm determines a final metering rate for each 20 second interval by comparing metering rates computed for local responsive conditions, queue override requirements, and system-wide conditions (“Helper” logic).

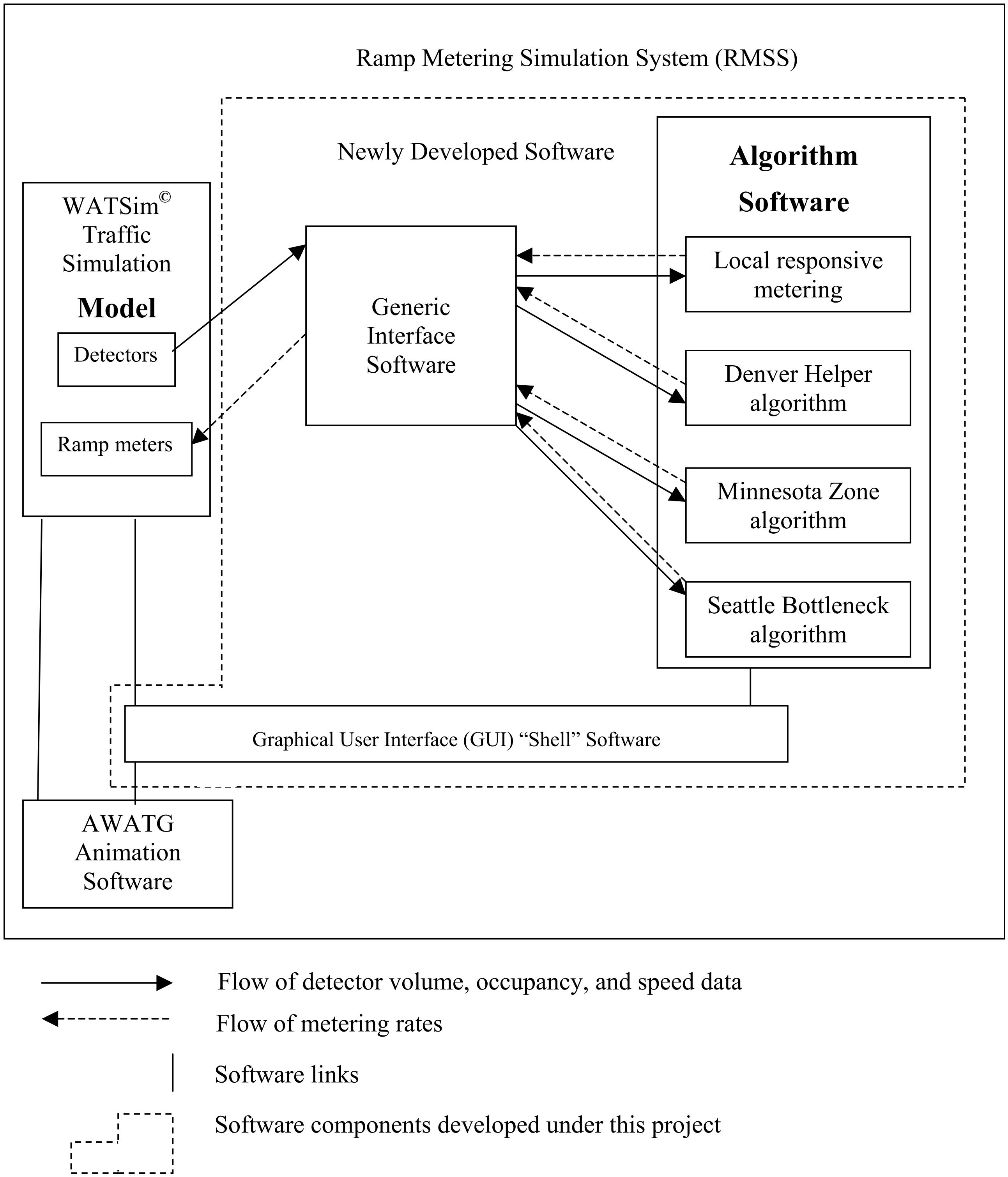


Figure E.1 Schematic of Ramp Meter Simulation System (RMSS).

Like the Denver algorithm, the Seattle Bottleneck algorithm uses three different processes to determine the metering rate for each ramp every 20 seconds. These include a local responsive rate, a rate based on the mainline flow through a bottleneck point within the system, and adjustments to these rates based on conditions, such as metering violations, queue overflows, etc.

The Minnesota Zone algorithm determines metering rates every 30 seconds based on two separate calculations. The first determines rates that would balance the in-flow and out-flow of each user defined "Zone." The second uses a form of localized traffic responsive control to account for localized impacts at individual ramps. Innovations to this algorithm that were recently developed and tested in Minneapolis are not included in this implementation of the algorithm.

Generic Interface Software

As shown in Figure E.1, the sensor data provided by the simulator includes occupancy, volume, and average speed. While each of the four algorithms requires detector occupancy data, the Seattle and Minnesota algorithms also use volume data, while the Denver algorithm additionally requires average speed data. The interface software transfers this detector data from the WATSim© simulator to the selected ramp meter algorithm every 20 or 30 seconds, depending on the algorithm. Only one algorithm can be run at a time. Similarly, the interface software returns the metering rates computed by the selected algorithm to the simulator for the next processing interval.

Graphical User Interface (GUI)

The GUI serves as a "shell" or supervisor for all other components of the RMSS. It enables users to access previously defined files, specify algorithm specific parameters, launch a run, or review results. It also includes a Help feature to assist in operating the system.

An extensive portion of the GUI code is devoted to specifying the parameters required for each metering algorithm. A step-by-step review of this process is described in Appendix D. Each algorithm has its own set of required data as described below in Section E.3. Once these data are specified and saved for a specific algorithm and roadway system, they need not be reentered. The data can, however, be recalled and edited using the GUI to change specifications at any time.

Once all data are defined for WATSim© as described in Appendix D, and for the metering algorithms as described in Appendix F, the GUI is used to select both the desired simulation case (such as AM or PM conditions) and metering algorithm, and initiate the simulation run.

At the conclusion of a run, the GUI provides access to intermediate and final results of the metering computations. These results can be viewed in html, spreadsheet, or text format. The results for any algorithm include current time, detector occupancies, and computed metering rates. Results of intermediate computations specific to each algorithm are also provided. A sample of the available output from each metering algorithm is contained in Appendix F.

The GUI is also used to launch software (known as AWATG) to provide an aerial overhead animation display of the traffic movements previously simulated by WATSim©. A sample frame from this animated display is shown in Figure E.2.

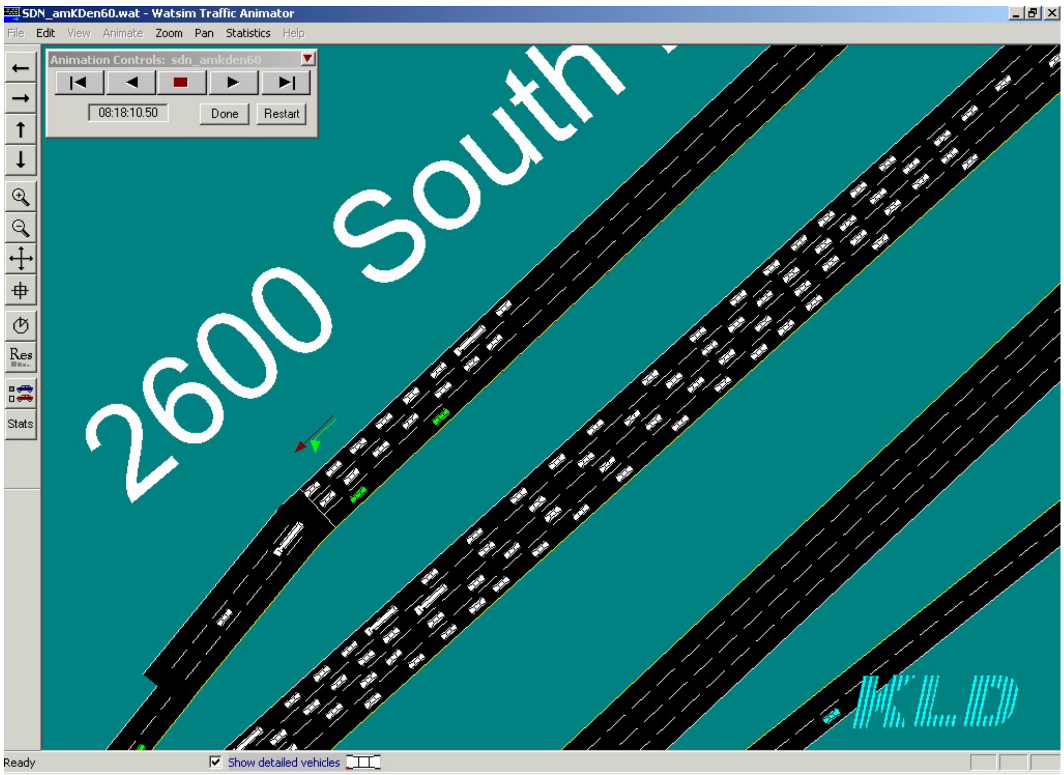


Figure E.2 Sample AWATG animation frame displaying operation of ramp meter.

E.1 Detector and Ramp Meter Coding

Chapter 6 discusses the details of WATSim© model coding and related issues. In this section the locations of detectors and ramp meters are presented for each of the three algorithms evaluated (see Appendices A to C for details on the algorithms).

E.1.1 Detector Requirements for Denver Helper algorithm

Figure E.3 shows the detector needs for the Denver Helper algorithm to meter ramps along the study roadway southbound during the AM peak. The Denver Helper algorithm requires three detectors per on-ramp: an upstream mainline detector nearest to each ramp entrance (M), an advance queue detector at the head of each ramp (Adv), and an intermediate queue detector in the middle of each ramp (Int). These detectors are shown in black dots in the figure, together with a ramp meter.

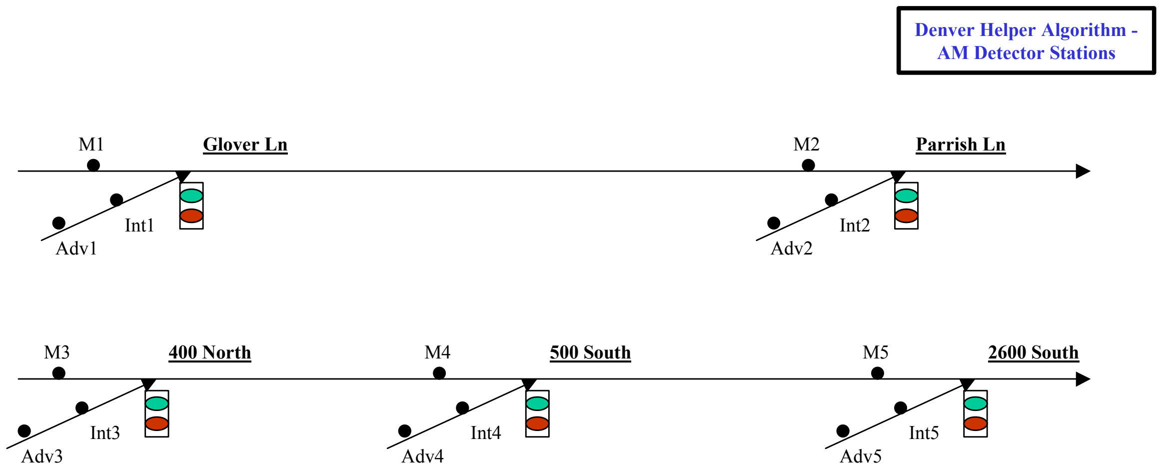


Figure E.3 Detector locations for Denver Helper algorithm.

E.1.2 Detector Requirements for Minnesota Zone algorithm

Figure E.4 shows the detector requirements to apply the Minnesota Zone algorithm to ramps within the study area in the southbound direction during the AM peak. This algorithm requires four detectors per on-ramp: an upstream mainline detector nearest to each ramp entrance (M), a downstream detector between the interchanges (D), a passage detector located just past the stop bar on each entrance ramp (P), and an off-ramp detector on the off-ramp right downstream of the on-ramp under consideration (X). These detectors are shown in black dots in the figure, together with a ramp meter.

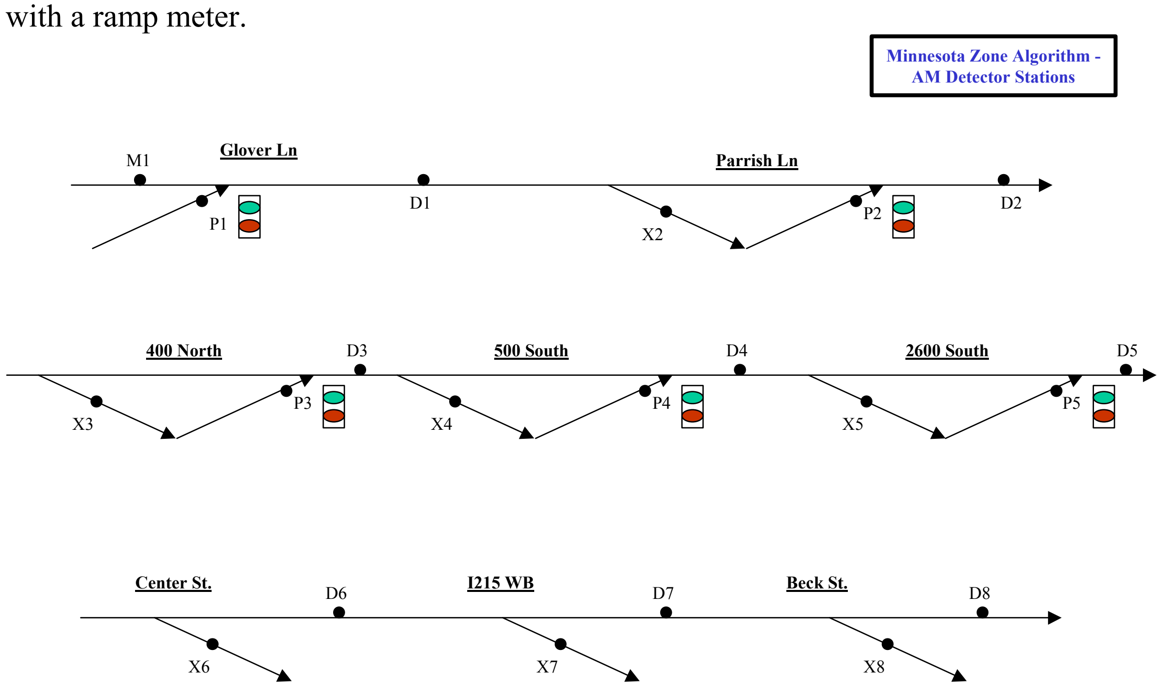


Figure E.4 Detector locations for Minnesota Zone algorithm.

E.1.3 Detector Requirements for Seattle Bottleneck algorithm

Figure E.5 shows the detector needs to meter ramps for southbound travel in the study area using the Seattle Bottleneck algorithm during the AM peak. The Seattle Bottleneck algorithm requires six detectors per on-ramp: an upstream mainline detector nearest to each ramp entrance (M); an advance queue detector at the head of each ramp (Adv); an intermediate queue detector in the middle of each ramp (Int); a passage detector located just past the stop bar on each entrance ramp (P), a downstream detector between the interchanges (D); and an off-ramp detector on the off-ramp downstream of the on-ramp under consideration (O). These detectors are shown in black dots in the figure, together with a ramp meter.

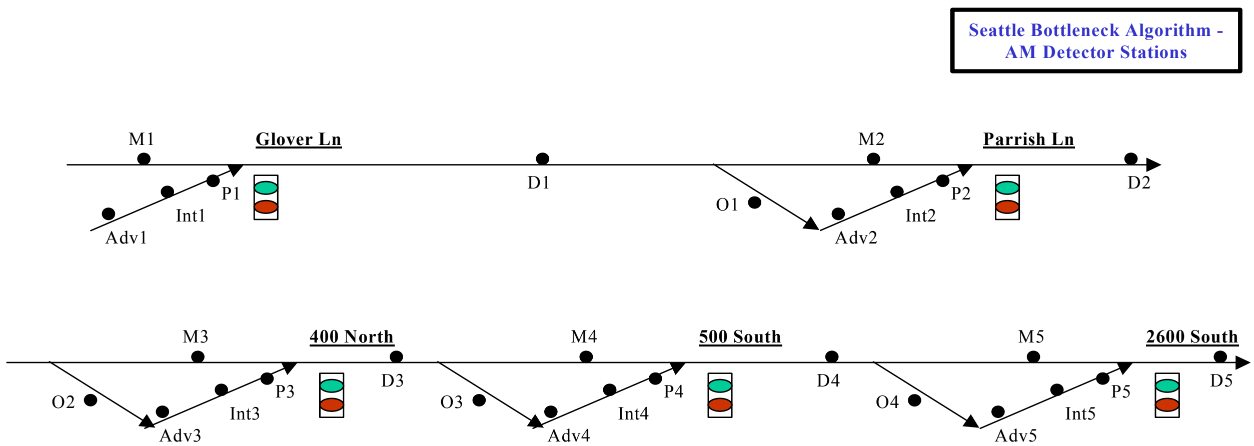


Figure E.5 Detector locations for Seattle Bottleneck algorithm.

E.2 Running the Ramp Meter Software

Before using the RMSS software, a WATSim© data file must be created for a simulation case as described in Appendix D. This file defines the geometry of the roadway system, the location of all detectors, traffic volumes, etc. Under this project, separate files have been created for each metering algorithm to reflect the specific detector requirements of the algorithm as indicated in Figures E.3 – E.5. Two variations of each algorithm specific file were created to represent AM peak and PM peak volumes respectively. An entry at the beginning of each file indicates the metering algorithm to be applied to the case. This entry is placed in the first columns of the first Type 00 record in the file as indicated in Table E.1.

Notice that Record Type 00 requires alphanumeric data; it can be letters or numbers as long as the column 79 and 80 of Record Type 00 has zeros. Therefore it is recommended to enter the data as shown in Table E.1.

Table E.1 Identifying the metering method by a number in Record Type 00.

Metering method	Number in column 1 of First Record Type 00	Example of the first few columns of first Record Type 00
Local responsive method	1	1Local
Denver algorithm	1	1Denver
Seattle algorithm	2	2Seattle
Minnesota algorithm	3	3Minnesota

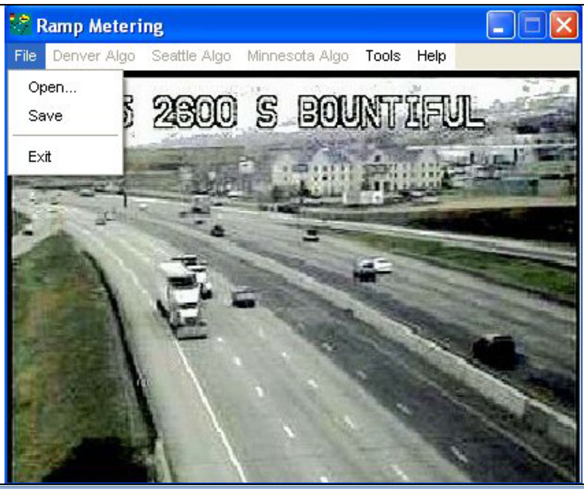
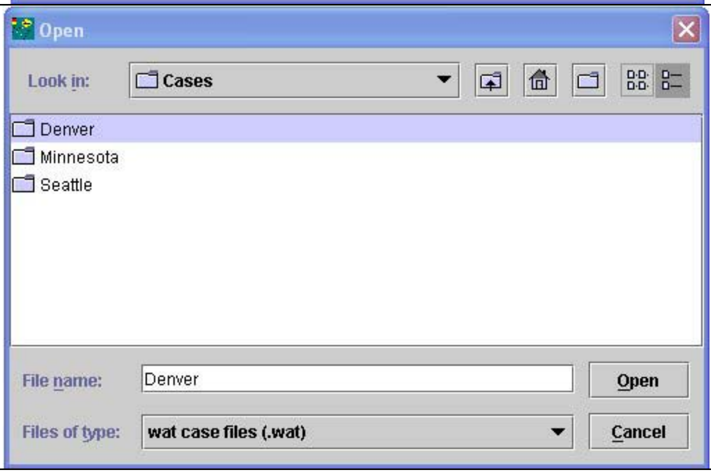
e.g.: `1Denver             I-15 Davis Co., UT    a.m. data, 6:00 - 9:00          00`

Once a WATSim© data file is completed, the RMSS software can be run for the metering algorithm specified in the data file. Note that cases without ramp metering can be simulated exclusively with WATSim© without using the RMSS. To launch the software, double-click on the Ramp Meter icon  Ramp Metering.lnk on the desktop. Follow the steps in Table E.2 to select a case for analysis. Once a case is selected, a menu for the appropriate metering algorithm is enabled allowing the user to specify or edit algorithm specific information; run the simulation; or review results (see Appendix F for details).

Table E.2 Steps to run the Ramp Meter Simulation System.

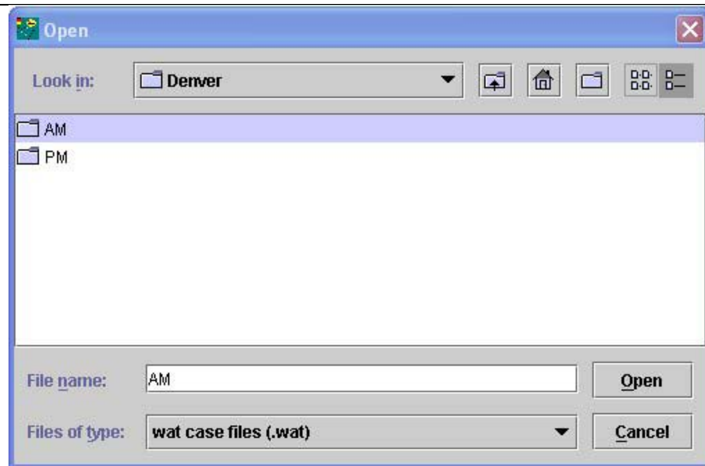
<table>
<tr>
<td>Step 1: Click the Ramp Meter icon to begin the Ramp Meter software.

The figure on the right appears when the software is launched. As this figure shows the software has 6 options in the main menu: File, Denver Algo(rithm), Seattle Algo(rithm), Minnesota Algo(rithm), Tools, and Help.</td>
<td>
</td>
</tr>
</table>

Step 2: Select File Open to begin. First the user needs to find the **.wat** file that is a WATsim model file containing necessary data for the case. Files are specific to the algorithm and peak period to be simulated.	
Step 3: Find the directory where the file is stored. In this example, it is stored in the Cases directory.	
Step 4: Find the directory where the file is stored (continued). When there are subdirectories, the user must search through subdirectories for the desired file.	

Step 5: Find the directory where the file is stored (continued).

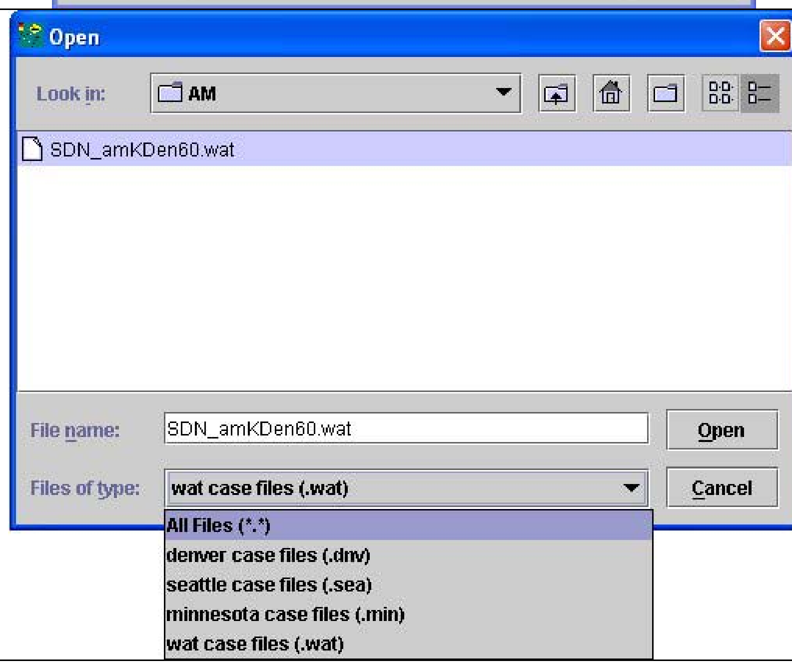
In this example the desired file is stored in the AM subdirectory within the Denver subdirectory, which is found in the Cases directory.



Step 6: Once the desired .wat file is located, select it.

The Open File option shows file types other than .wat files. In this case, the file type is “wat cases files (.wat).”

The file with extension .dnv contains parameters specific to the operation of the Denver algorithm. Similarly, a file with extension .sea is for the Seattle algorithm, and one with extension .min is specific to the Minnesota Zone algorithm.



E.3 Entering Necessary Data to Simulate Ramp Meter Algorithms

Each of the four ramp-metering methods has a set of data requirements to compute metering rates. This includes identifying the set of detectors in the WATSim© file associated with each ramp, and the function of each of these detectors for the metering computations (Mainline, Intermediate, etc.). Other requirements include calibration parameters specific to the operation of an algorithm, such as zonal capacity for the Minnesota algorithm. As previously indicated, the GUI of the RMSS is used to specify this algorithm-specific information. Step-by-step procedures to enter this information for each algorithm are contained in Appendix F.

For example, the GUI provides a menu for the Denver algorithm to specify:

- Ramp data—identifying the WATSim© detectors associated with each ramp and the function of each detector (Mainline, Advance, Intermediate).
- Group data—the list of ramps and the sequence they will be processed by the system-wide "Helper" logic to adjust metering rates on upstream ramps when downstream flow becomes congested.
- Rate data—the relationships between detector occupancies and metering rates.
- Timer table—defining how long it takes after congested conditions occur downstream, for metering rates to be reduced at upstream ramps.
- Upstream time—defining the rate at which upstream metering rates are reduced over time to respond to downstream congestion.

The GUI is used for the Seattle algorithm to define:

- The detectors associated with each ramp (Passage, Intermediate, Advanced, Off-ramp, Mainline, and Downstream).
- The boundaries of each roadway section and the set of mainline ramps within the section.
- Weighting factors used for the computations.
- The relationship between detector occupancies and metering rates.

Similarly, the GUI is used for the Minnesota Zone algorithm to identify:

- The detectors associated with each ramp (Passage, Off-ramp, Mainline, Downstream).
- The target value of metered entrance ramp volumes over a 5-minute period.
- Calibration constants for the computations.
- Zone capacity (vehicles/zone).
- The relationship between detector occupancies and metering rates.
- The detectors and ramps within each zone.

Once specified, the algorithm specific information is stored in a file called <casename>.<ext> where <casename> is the same name as the WATSim© name for the case, and <ext> is either dnv, sea, or min, for the Denver, Seattle, and Minnesota algorithms respectively. These files have already been created for all cases performed under this study and need not be edited with the GUI unless the user wants to change some of the algorithm specific parameters for experimental purposes.

When the algorithm-specific case file is complete, the GUI offers a command on the menu to run the simulation as shown for each algorithm in Appendix F.

E.4 Sample Output of WATSim©

WATSim© presents a variety of outputs that can be used for performance evaluation. Table E.3 presents a list of some of the MOEs that are available for comparative analyses. Measures for freeway segments include all of the measures available for surface street roadways plus two extra MOEs shown in Table E.3. All MOEs in the table are given for each link, and for the entire roadway network included in the analysis. These statistics are provided at user-specified intervals as well as for the entire duration of the run. Movement specific statistics for similar MOEs are also provided. Besides those listed in Table E.3, WATSim© provides separate statistics for buses, LRT, toll plazas, etc., when they are included in the simulation.

Table E.3 WATSim© output measures of effectiveness.

Surface Street Segments	Additional Freeway Segments Outputs
• Vehicle miles traveled • Vehicle trips that traveled the link • Move time (running time) in vehicle minutes, minutes/mile, and seconds/vehicle • Delay time in vehicle minutes, minutes/mile, and seconds/vehicle • Total travel time in vehicle minutes, minutes/mile, and seconds/vehicle • Ratio of move time over total travel time • Queue time in seconds/vehicle • Stop time in seconds/vehicle • Percent stop • Volume in vehicle per hour (vph) • Average speed in miles per hour (mph) • Fuel consumption and vehicle emissions output • Intersection statistics (vehicle trips, average stop delay in seconds, link level of service, intersection delay in seconds	• Density in vehicle/lane-mile (for the current time period and average up to the time period of interest) • Freeway level of service for the current time period and average up to the time period of interest)

Figures E.6 through E.8 show some of the outputs of the freeway links in the north end of the study area for southbound travel. Figure E.6 shows the main MOE section, Figure E.7 shows the extra MOE for freeway segments, and Figure E.8 shows emission related output.

In addition to these MOEs, the simulation produces a set of files describing vehicle trajectories, which is used by the AWATG software to produce an animated display of simulated traffic operations.

CUMULATIVE WATSIM STATISTICS AT TIME 7:45: 0

ELAPSED TIME IS 1:45: 0 (6300 SECONDS), TIME PERIOD 7 ELAPSED TIME IS 900 SECONDS

LINK	VEHICLE MILES	VEHICLE TRIPS	VEHICLE MINUTES MOVE TIME	VEHICLE MINUTES DELAY TIME	VEHICLE MINUTES TOTAL TIME	RATIO MOVE/ TOTAL	MINUTES/MILE TOTAL TIME	MINUTES/MILE DELAY TIME	SECONDS / VEHICLE TOTAL TIME	SECONDS / VEHICLE DELAY TIME	SECONDS / VEHICLE QUEUE TIME	SECONDS / VEHICLE STOP TIME	AVERAGE VALUES STOPS (%)	AVERAGE VALUES VOLUME VPH	AVERAGE VALUES SPEED MPH
(8100, 100)		2880												1645	
(100, 101)	544.98	2878	504.8	60.2	565.0	0.89	1.04	0.11	11.8	1.3	0.0	0.0	0	1644	57.9
(101, 102)	190.73	2518	176.7	21.1	197.8	0.89	1.04	0.11	4.7	0.5	0.0	0.0	0	1438	57.9
(102, 103)	1795.18	2708	1662.9	138.9	1801.8	0.92	1.00	0.08	39.9	3.1	0.0	0.0	0	1547	59.8
(103, 104)	1734.99	2686	1607.1	135.2	1742.3	0.92	1.00	0.08	38.9	3.0	0.0	0.0	0	1534	59.7
(104, 105)	885.89	2933	820.6	75.5	896.1	0.92	1.01	0.09	18.3	1.5	0.0	0.0	0	1676	59.3
(105, 106)	1051.89	2914	974.4	81.8	1056.2	0.92	1.00	0.08	21.7	1.7	0.0	0.0	0	1665	59.8
(106, 107)	1111.02	2904	1029.2	87.5	1116.7	0.92	1.01	0.08	23.1	1.8	0.0	0.0	0	1659	59.7
(107, 108)	761.87	2894	705.7	68.4	774.2	0.91	1.02	0.09	16.1	1.4	0.0	0.0	0	1653	59.0
.															
.															
.															
.															
(8680, 680)		97												55	
(680, 670)	6.43	97	12.9	6.6	19.5	0.66	3.03	1.03	12.1	4.1	2.2	2.2	100	55	19.8
(670, 671)	1.02	54	2.0	4.5	6.6	0.31	6.40	4.40	7.3	5.0	3.1	2.3	100	30	9.4
(671, 670)	1.02	54	2.0	3.5	5.6	0.37	5.46	3.46	6.2	3.9	2.2	2.1	100	30	11.0
(670, 680)	8.44	128	16.9	5.5	22.4	0.75	2.65	0.65	10.5	2.6	0.3	0.0	0	73	22.6
NETWORK=	111609.0	19985	1873.04	330.86	2203.90	0.85	1.18	0.18	6.62	0.99	0.23	0.21	1.0		50.6
			-- VEHICLE - HOURS --						--- MINUTES / VEHICLE-TRIP ---				PER TRIP		

Figure E.6 Cumulative WATSim© statistics.

WATSIM FREEWAY LOS STATISTICS AT TIME 7:45: 0

ELAPSED TIME IS 1:45: 0 (6300 SECONDS), TIME PERIOD 7 ELAPSED TIME IS 900 SECONDS

LINK	CURRENT DENSITY VEH/LA-MI	CURRENT FREEWAY LOS	AVERAGE DENSITY VEH/LA-MI	AVERAGE FREEWAY LOS
(100, 101)	12.3	B	9.7	A
(101, 102)	19.8	C	15.8	B
(102, 103)	13.1	B	8.9	A
(103, 104)	13.4	B	8.8	A
(104, 105)	11.3	B	5.9	A
(105, 106)	10.5	B	5.8	A
(106, 107)	6.8	A	5.8	A
(107, 108)	9.1	A	6.0	A

Figure E.7 Additional MOEs for freeway segments.

1 CUMULATIVE VALUES OF FUEL CONSUMPTION AND OF EMISSIONS

LINK	FUEL CONSUMPTION GALLONS AUTO	GALLONS TRUCK	GALLONS BUS	M.P.G. AUTO	M.P.G. TRUCK	M.P.G. BUS	VEHICLE EMISSION RATES (KG/MILE.HOUR) HC	CO	NO X
(8100, 100)									
(100, 101)	22.3	2.2	0.0	18.1	9.6	0.0	0.186	7.570	0.995
(101, 102)	6.6	1.1	0.0	22.6	7.3	0.0	0.114	2.677	0.612
(102, 103)	61.8	10.4	0.0	22.0	7.2	0.0	0.129	3.790	0.665
(103, 104)	55.5	10.0	0.0	23.6	7.2	0.0	0.116	3.071	0.571
(104, 105)	29.8	5.6	0.0	22.5	7.0	0.0	0.136	4.023	0.687
(105, 106)	33.6	6.5	0.0	23.6	7.2	0.0	0.126	3.400	0.617
(106, 107)	36.8	6.9	0.0	22.7	7.2	0.0	0.136	4.111	0.660
(107, 108)	26.7	4.7	0.0	21.5	7.1	0.0	0.154	5.606	0.728

Figure E.8 Emission related outputs

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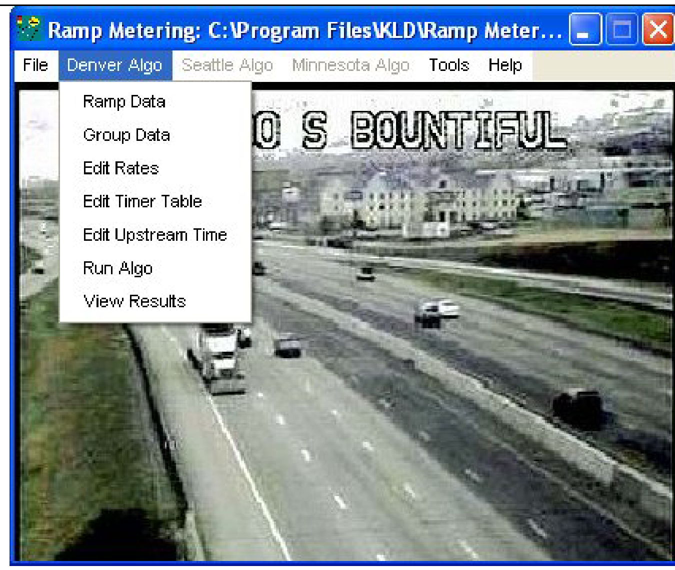
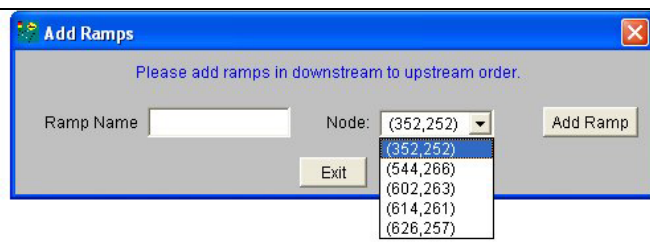
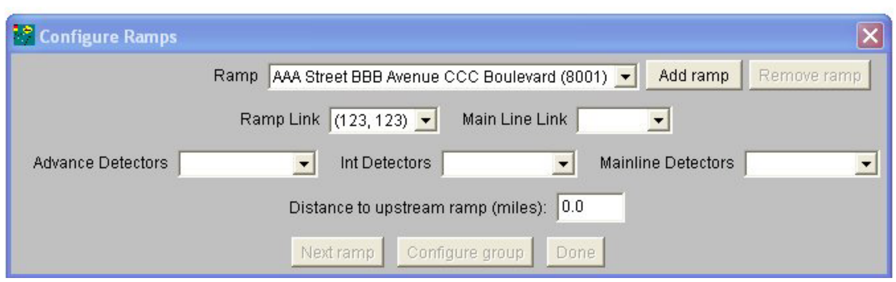
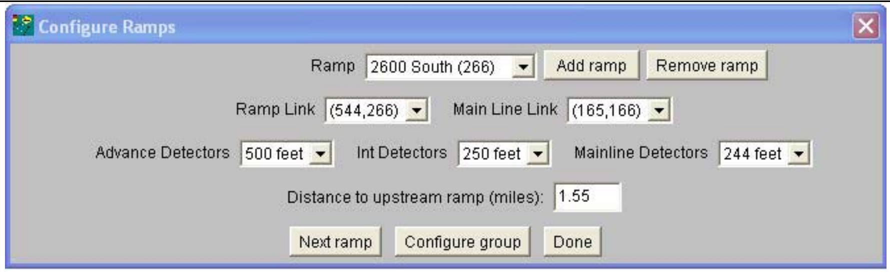
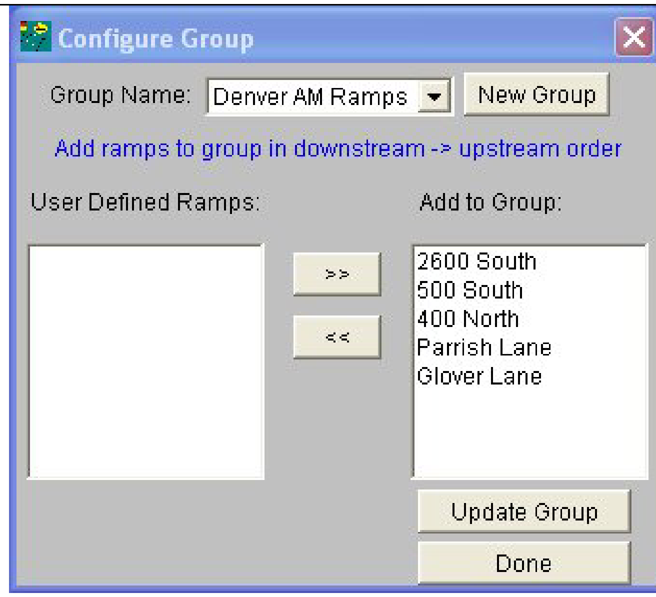
APPENDIX F – STEPS FOR ENTERING NECESSARY DATA INTO RMSS

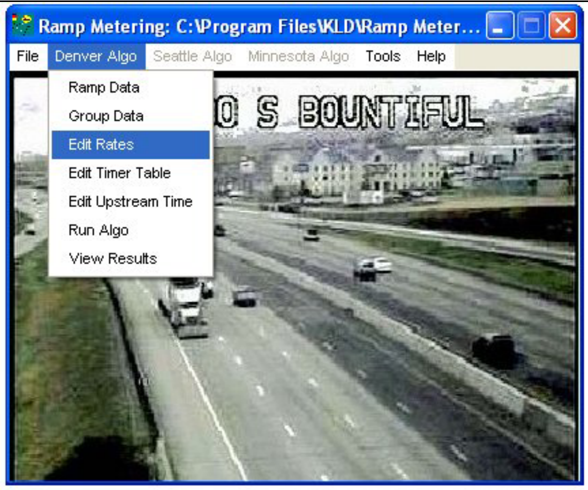
Each algorithm requires different types of information. This appendix shows the steps to enter necessary data in the Ramp Metering software for the three ramp meter algorithms tested. Please note that the local responsive case is the first portion of the Denver algorithm. The Ramp Meter software asks whether the user wants to run the local responsive metering case or the Denver Helper algorithm. Refer to Appendix A through C for the detail of input requirements.

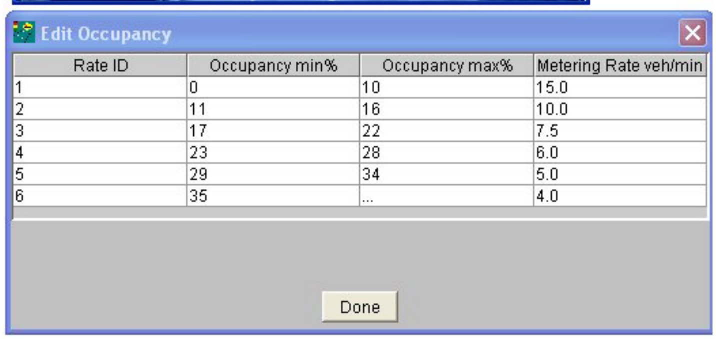
F.1 Local Responsive Meter Case and the Denver Helper Algorithm

Step 1. Select the Denver Algo menu to see the data entry options for the Denver method. The Denver Algo menu is highlighted once you select a .wat file that contains a number 1 in the first column of Record Type 00.	
Step 2. Select the Ramp Data option and add ramps included in the analysis. The dialog window shown above appears in the monitor. Links (shown by two nodes) containing a ramp are listed in the Node cell. Add ramps in downstream to upstream order; add names accordingly.	

Step 3. Select the Configure ramps option and enter necessary detector information, the main line link that the ramp link will feed into, and other necessary information shown in the figure to the right.	
Step 4. Select the Configure Group option and give a analysis group name. When the freeway segment is being analyzed, there may be multiple meter "groups." The segment used for the study was about 10 miles; hence there was only one group. Select ramp names from the User defined ramps section to the Add to Group section by using the proper arrow buttons.	

Step 5. Select the Edit metering rates option and enter mainline minimum and maximum occupancy values and metering rates for each level of occupancy upstream of the ramp, as shown in the figure to the right. See Appendix A for the values used for this study.



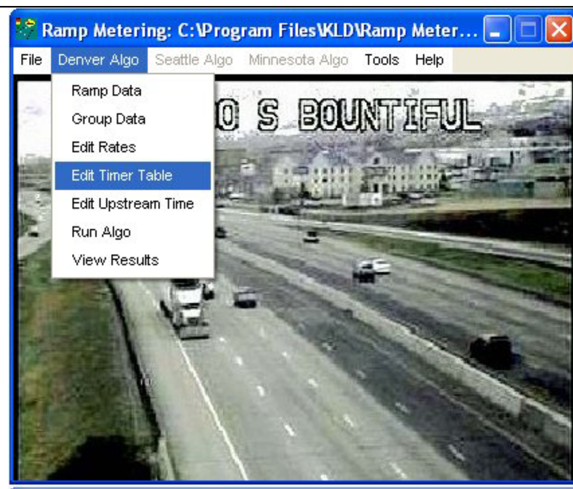


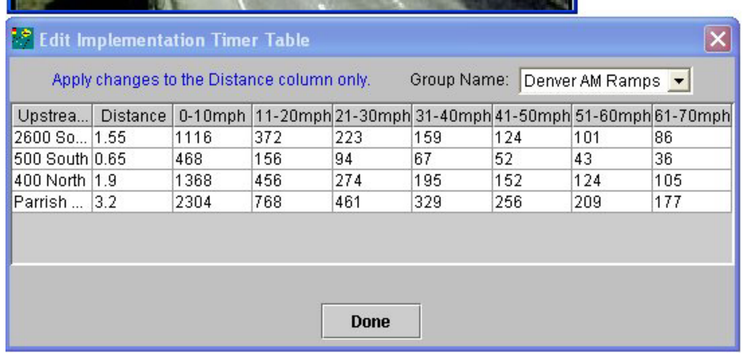
Edit Occupancy

Rate ID	Occupancy min%	Occupancy max%	Metering Rate veh/min
1	0	10	15.0
2	11	16	10.0
3	17	22	7.5
4	23	28	6.0
5	29	34	5.0
6	35	...	4.0

Done

Step 6. Edit timer table for the Helper algorithm to function. The user enters the distance between the two adjacent ramps. The ramps are listed from upstream to downstream. Hence the first ramp entered appears at the bottom of the list. For instance, between 500 South and 2600 South is 1.55 miles. Timer values are computed by dividing the distance by the mid value of the speed range multiplied by 3600, e.g. 1.55 mile/5 mph (for 0 to 10 mph) x 3600 sec/hr = 1,116 seconds.





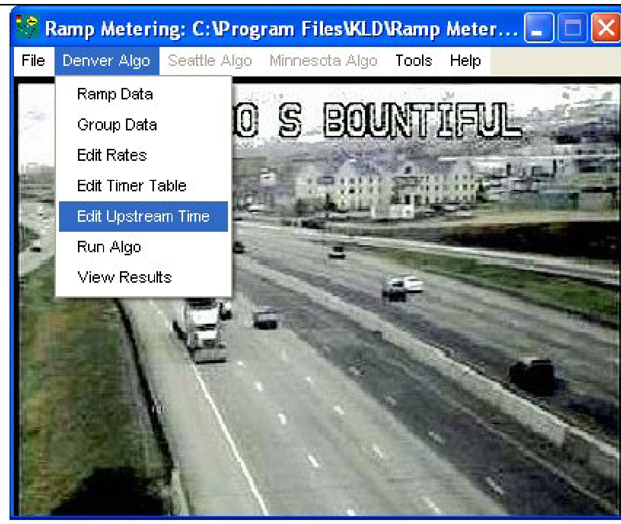
Edit Implementation Timer Table

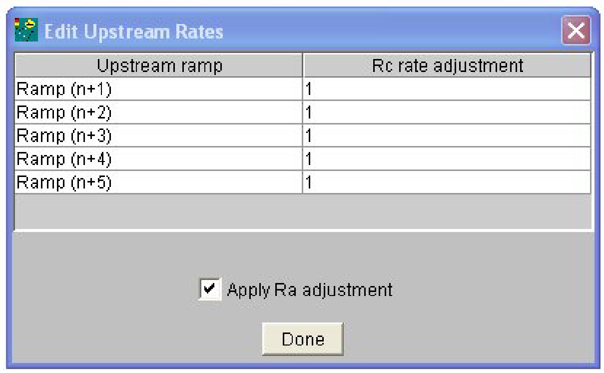
Apply changes to the Distance column only. Group Name: Denver AM Ramps

Upstrea...	Distance	0-10mph	11-20mph	21-30mph	31-40mph	41-50mph	51-60mph	61-70mph
2600 So...	1.55	1116	372	223	159	124	101	86
500 South	0.65	468	156	94	67	52	43	36
400 North	1.9	1368	456	274	195	152	124	105
Parrish ...	3.2	2304	768	461	329	256	209	177

Done

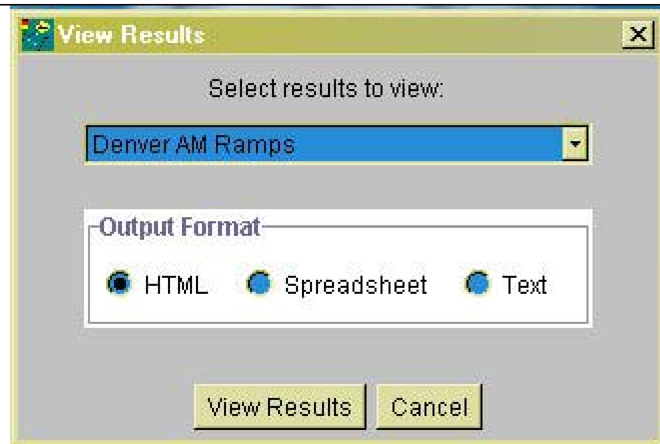
Step 7. Select the Edit upstream rates option (or "timing" rates of the ramp meter) and enter Rc adjustment rates for upstream ramps. One level stricter metering rate was entered for this study. See Appendix A for Rc values used for this study. Metering rate is one level more restrictive.





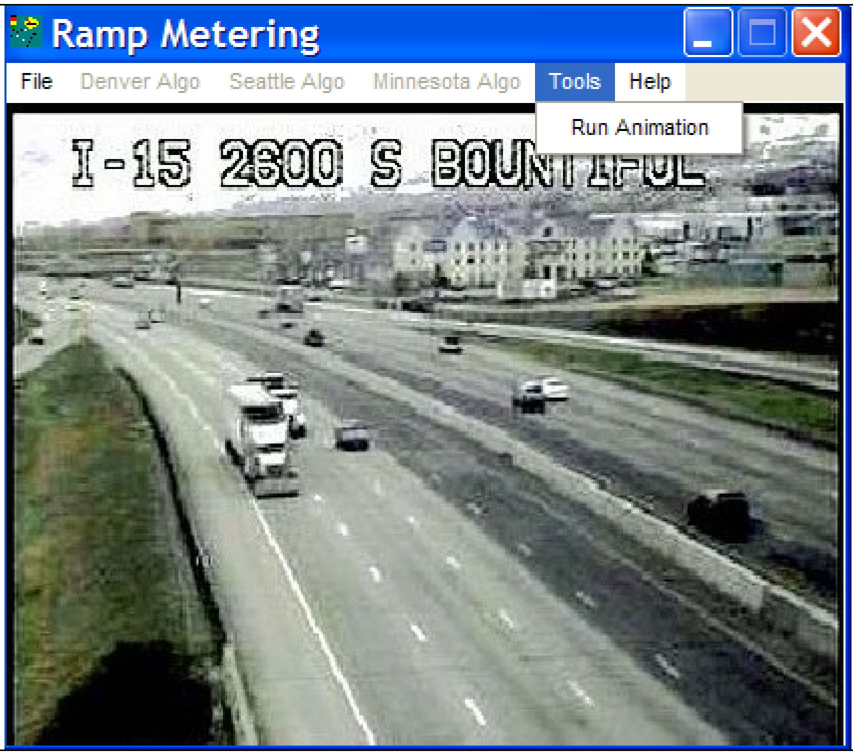
Step 8. Select Run algorithm to run the Denver metering algorithm, including the Helper algorithm. If the local responsive metering is simulated, select the Enable Local Metering option first before the **Run Watsim** is selected.

Step 9. Select View Results to see the metering rate status at every 20-second interval after WATSim has been run. As shown to the right, the results come in three formats: HTML, Spreadsheet, or Text format. Select the one most convenient. The spreadsheet format can be useful for statistical analyses. The HTML format is shown here.



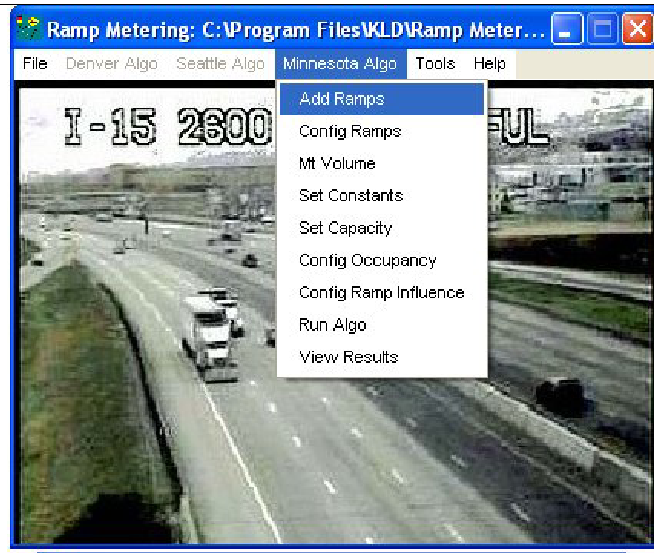
Denver Algorithm Results

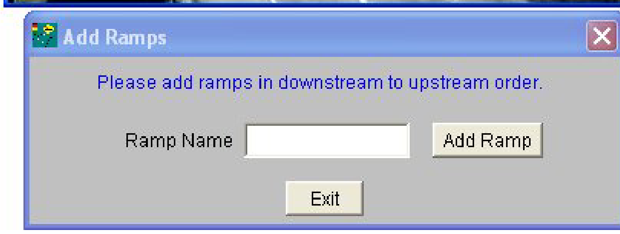
Time (secs)	Ramp Name	R_a	R_b	R_c	MainLine Occ.	Intermediate Occ.	Advanced Occ.	MainLine Speed	Ramp Critical	FinalRate
0	2600 South	1	0	1	0	0	0	0	false	15.0
0	500 South	1	0	1	0	0	0	0	false	15.0
0	400 North	1	0	1	0	0	0	0	false	15.0
0	Parrish Lane	1	0	1	0	0	0	0	false	15.0
0	Glover Lane	1	0	1	0	0	0	0	false	15.0
20	2600 South	1	0	1	0	0	1	0	false	15.0
20	500 South	1	0	1	0	0	4	0	false	15.0
20	400 North	1	0	1	0	2	4	0	false	15.0
20	Parrish Lane	1	0	1	0	0	2	0	false	15.0
20	Glover Lane	1	0	1	0	0	0	0	false	15.0
40	2600 South	1	0	1	0	0	1	0	false	15.0
40	500 South	1	0	1	0	0	0	0	false	15.0

Step 10. Select Tool-Animation to see WATSim animation of the simulation.	

F.2 Minnesota Zone Algorithm

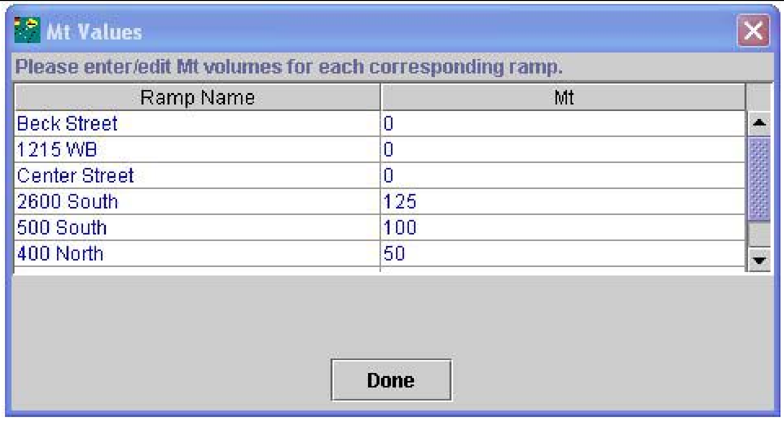
Step 1. Select the Minnesota Algo menu to see the data entry options for the Minnesota ramp metering method. The Minnesota Algo menu is highlighted once you select a .wat file that contains a number 3 in the first column of Record Type 00. Select **Add Ramps** to tell the Ramp Meter software which ramps containing the meter are included in the analysis by giving the node numbers and a ramp name. Links (shown by two nodes) containing a ramp are listed in the Node section. Once all the necessary ramps are entered, select **Exit**.



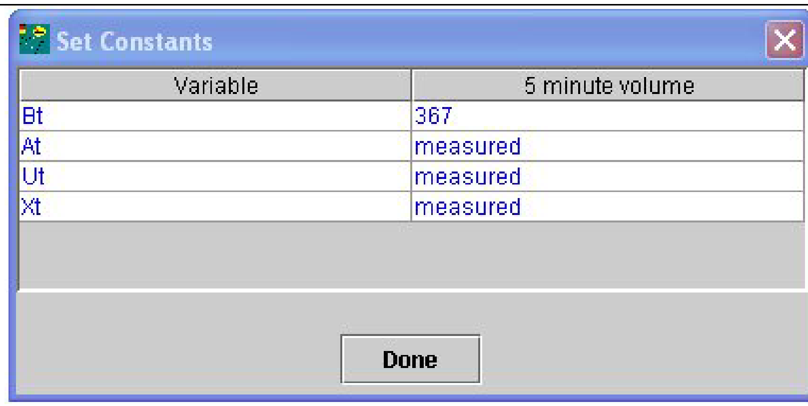


Step 2. Select the Configure ramps option to configure each ramp metering setup. As shown in the figure to the right, the Minnesota algorithm requires 4 detectors for each ramp. Once all the information is entered, select **Exit**.

Step 3. Select the Mt Values option and enter Mt values defined by the user. Mt values are "target" values of M that is the total of the metered entrance volumes in the section. See Appendix C for details.

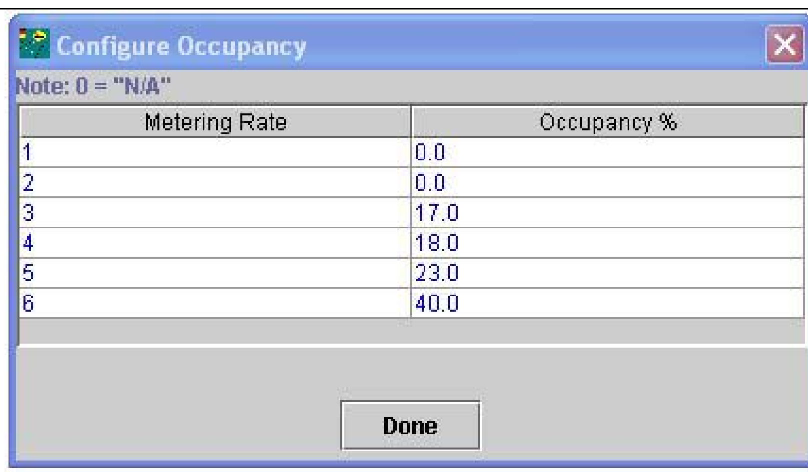


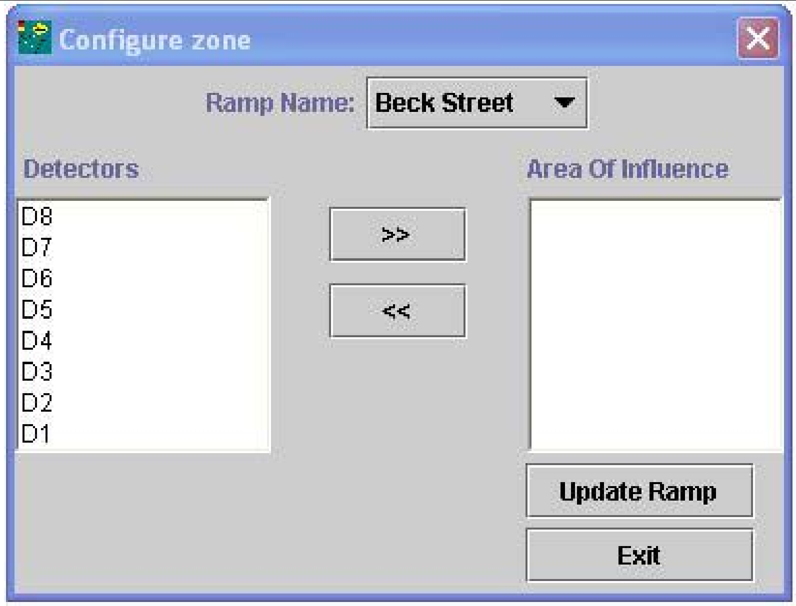
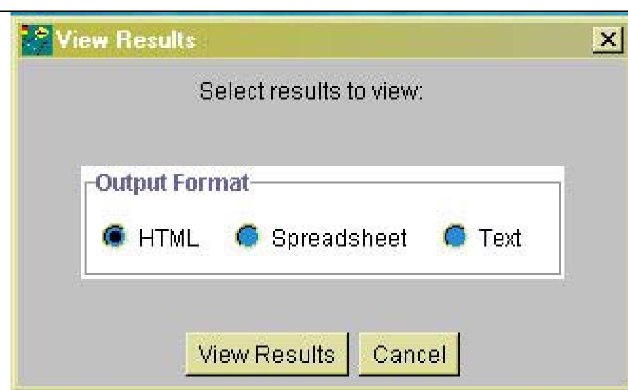
Step 4. Select the Set Constants and enter constant values for the variables using in the Minnesota algorithm. See Appendix C for the definitions of the variables.



Step 5. Select the Zone Capacity option and enter the capacity for the zone expressed in terms of density per zone.

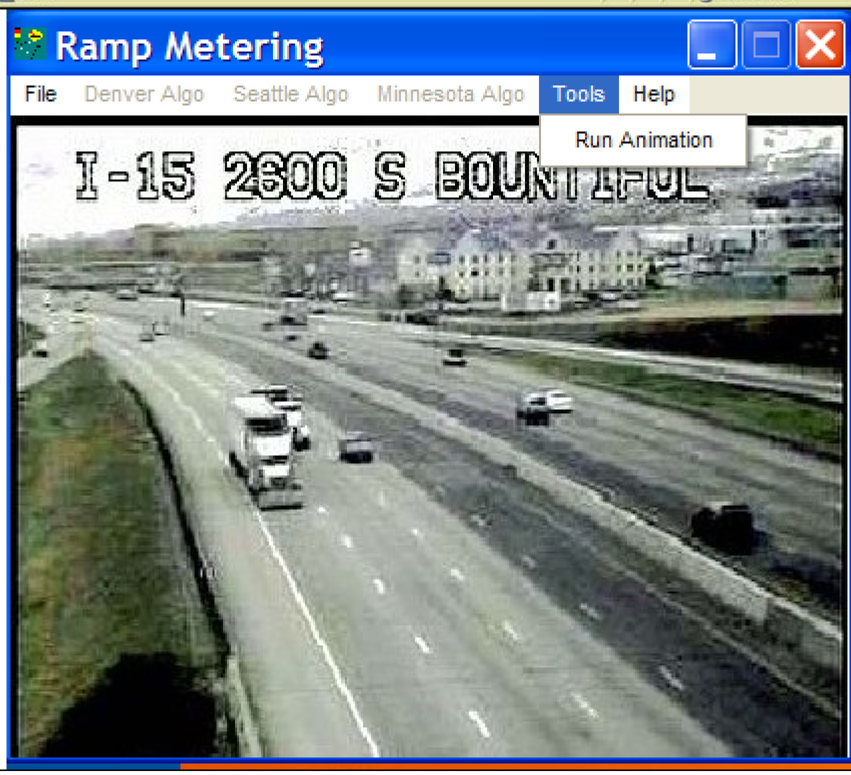
Step 6. Select the Configure Occupancy option and enter occupancy threshold for metering rate level. Metering rate 1 is the least restrictive and metering rate 6 is the most restrictive.



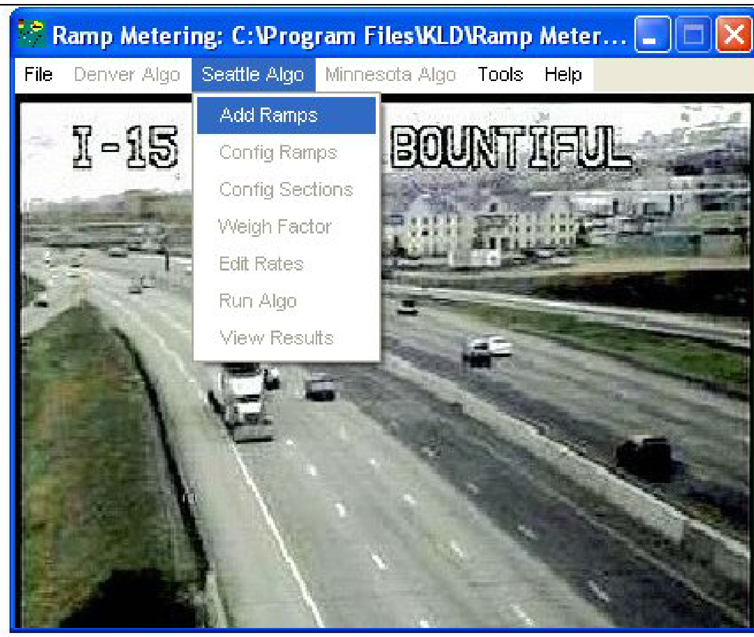
Step 7. Select the Configure zone option and enter the detection area of influence (in terms of detectors). See Appendix C for details. For instance, the Beck Street ramp meter's influence area contains detectors D9 and D10. The user selects D9 and clicks the right-arrow button to include it in the area of influence.	
Step 8. Select Run algorithm to run the Minnesota algorithm. Once the WATSim run has been completed, the user can see the metering status at every 30-second interval by selecting the **View results** option.	
Step 9. Select View Results to see the metering rate status at every 30-second interval after WATSim has been run. As shown to the right, the results come in three formats: HTML, Spreadsheet, or Text format. Select the one most convenient. The spreadsheet format can be useful for statistical analyses. The HTML format is shown here.	

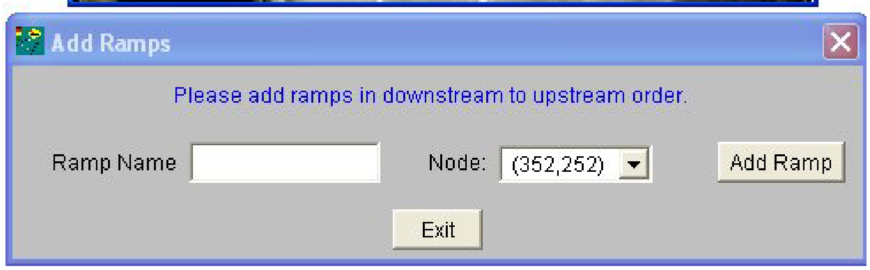
Time(secs)	Ramp Name	S	X+B+S-(A+U)	Mt	red time	ramp rate	zone rate	vpm
0	Parrish Lane	1296	1833	71	2	1	1	15
0	Hwy 89	1296	1833	71	2	1	1	15
0	500 South	1296	1833	38	3	1	1	15
0	2600 South	1296	1833	47	2	1	1	15
0	Beck Street	1296	1833	121	2	1	1	15
30	Parrish Lane	1296	1809	71	2	1	1	15
30	Hwy 89	1296	1809	71	2	1	1	15
30	500 South	1296	1809	38	3	1	1	15
30	2600 South	1296	1809	47	2	1	1	15
30	Beck Street	1296	1809	121	2	1	1	15
60	Parrish Lane	1290.5	1782.5	71	2	1	1	15
60	Hwy 89	1290.5	1782.5	71	2	1	1	15
60	500 South	1290.5	1782.5	38	3	1	1	15
60	2600 South	1290.5	1782.5	47	2	1	1	15
60	Beck Street	1290.5	1782.5	121	2	1	1	15

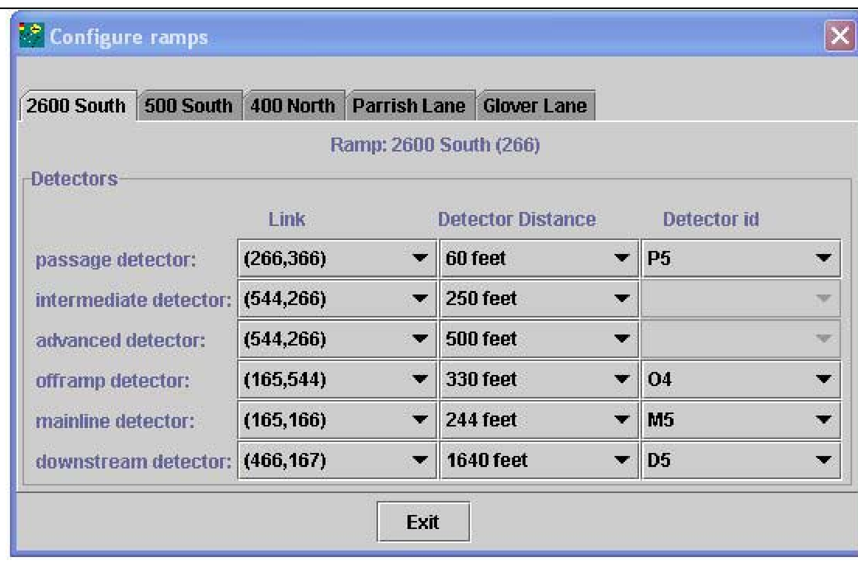
Step 10. Select Tools – Run Animation to see WATSim animation of the simulation.



F.3 Seattle Bottleneck Algorithm

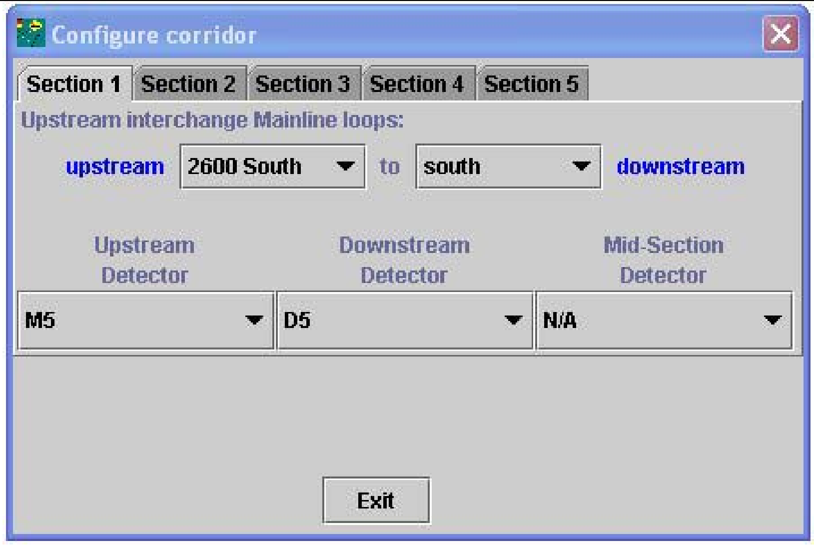
<table>
<tr>
<td>Step 1. Select the Seattle Algo menu to see the data entry options for the Denver method. The Denver Algo menu is highlighted once you select a .wat file that contains a number 2 in the first column of Record Type 00. Select Add Ramps to tell the Ramp Meter software which ramps containing the meter are included in the analysis by giving the node numbers and a ramp name. Links (shown by two nodes) containing a ramp are listed in the Node section. Once all the necessary ramps are entered, select Exit.</td>
<td>




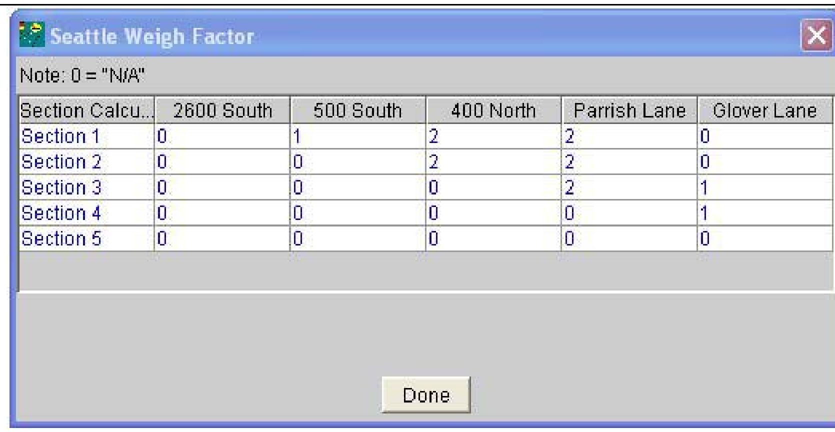
</td>
</tr>
<tr>
<td>Step 2. Select the Configure ramps option to configure each ramp metering setup. As shown in the figure to the right, the Seattle algorithm requires 6 detectors for each ramp. Once all the information is entered, select Exit.</td>
<td>


</td>
</tr>
</table>

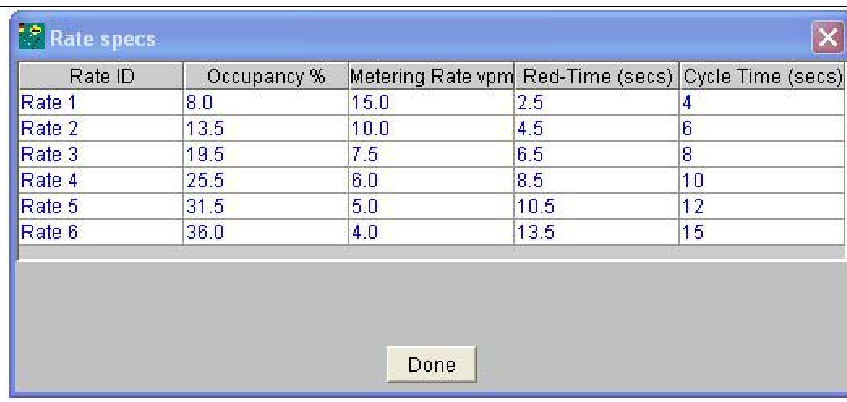
Step 3. Select the Configure corridor option. The Seattle Bottleneck algorithm requires that the ramps be grouped in sections. In this study, the sections were chosen as the portions of the mainline between two adjacent interchanges.



Step 4. Select the Seattle Weigh Factor option to define the weights for each ramp in a section. The Seattle algorithm requires that these weights used in its algorithm incorporate the effect of "excess storage" in the mainline traffic flow on metering ramp inflow.

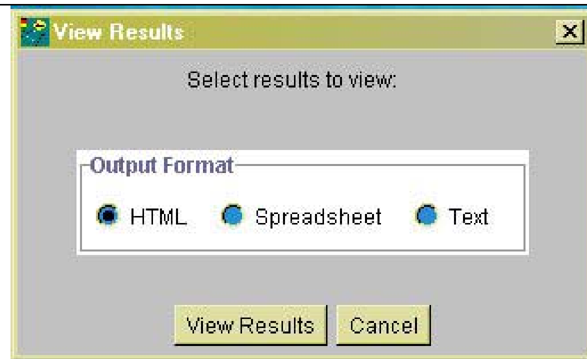


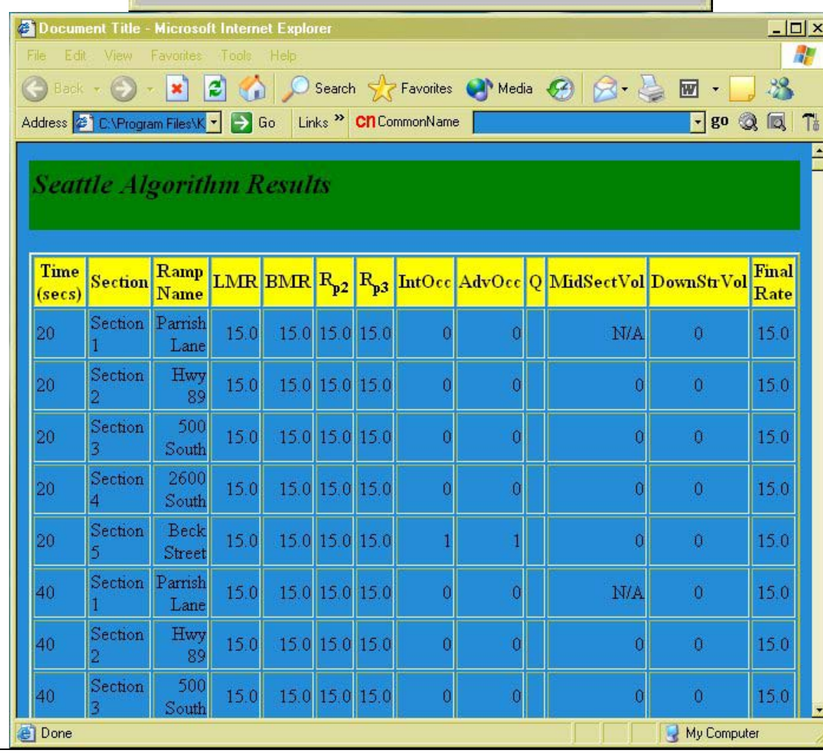
Step 5. Select the Edit rates option to define the conditions for each ramp meter rate. The program asks for information for six levels of metering rates. Each rate's upper threshold expressed by occupancy (%) needs to be entered, along with a metering rate, red-time length, and cycle time. Here the length of green time is 1.5 seconds.



Step 6. Select Run algorithm to run the Seattle algorithm. Once the WATSim run has been completed, the user can see the metering status at every 20-second interval by selecting the **View results** option.

Step 7. Select View Results to see the metering rate status at every 20-second interval after WATSim has been run. As shown to the right, the results come in three formats: HTML, Spreadsheet, or Text format. Select the one most convenient. The spreadsheet format can be useful for statistical analyses. The HTML format is shown here.





Time (secs)	Section	Ramp Name	LMR	BMR	R_{p2}	R_{p3}	IntOcc	AdvOcc	Q	MidSectVol	DownStrVol	Final Rate
20	Section 1	Parrish Lane	15.0	15.0	15.0	15.0	0	0		N/A	0	15.0
20	Section 2	Hwy 89	15.0	15.0	15.0	15.0	0	0		0	0	15.0
20	Section 3	500 South	15.0	15.0	15.0	15.0	0	0		0	0	15.0
20	Section 4	2600 South	15.0	15.0	15.0	15.0	0	0		0	0	15.0
20	Section 5	Beck Street	15.0	15.0	15.0	15.0	1	1		0	0	15.0
40	Section 1	Parrish Lane	15.0	15.0	15.0	15.0	0	0		N/A	0	15.0
40	Section 2	Hwy 89	15.0	15.0	15.0	15.0	0	0		0	0	15.0
40	Section 3	500 South	15.0	15.0	15.0	15.0	0	0		0	0	15.0

Step 8. Select Tool – Run Animation to see WATSim animation of the simulation.